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SUDBURY ENVIRONMENTAL STUDY

1973-1980

Synopsis

Ontario
Ministry of the Environment

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This synoptic report has been prepared by the Acidic Precipitation in Ontario Study Coordination Office in order to consolidate the findings and summarize the conclusions of the series of in-depth studies undertaken in the Sudbury area from the period 1973 to 1980 as part of the Sudbury Environmental Study.

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SUDBURY ENVIRONMENTAL STUDY.

SYNOPSIS

1973-1980

OCTOBER 1982

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1. EXECUTIVE SUMMARY

Industrial activity in the Sudbury, Ontario area over a ninety year period, has resulted in significant environmental degradation.

From 1890 to 1929, approximately 28,000,000 tonnes of ore were processed with roughly 11,000,000 tonnes of sulphur dioxide being released to the atmosphere. Emissions to the atmosphere during the period from 1930 to 1982 have been estimated to be in the order of 94,000,000 tonnes of sulphur dioxide. These emissions, together with heavy deforestation and frequent forest fires, were the causal agents of the extensive environmental impact in the Sudbury area.

The impact of the sulphur dioxide emissions, as well as trace metal emissions, on the local environment resulted in detrimentally altered surficial soils, damaged, stunted and/or eliminated vegetative cover, many clear and fishless lakes and frequent, but seasonally dependent, fumigations.

The Ontario Ministry of the Environment, in attempting to better understand the Sudbury situation, undertook a series of special studies from 1973 to 1980, called the Sudbury Environmental Study (SES).

The objectives of the SES were:

1. To determine whether or not the emissions from the Sudbury area mining operations were adversely impacting the local environment and, if so, to what degree.

2. To determine the extent to which the emissions should be limited in order to ensure that:

   a) the reclamation accomplishments to date would not be reversed;
   b) no additional environmental damage due to the local sources ensues.

In order to meet the above objectives, the program which was developed needed to address several areas: emissions, meteorology and dispersion, atmospheric chemistry, removal and deposition, terrestrial and aquatic effects, and remedial measures.

This difficult task was complicated by the significant fluctuation in emissions during this time period, as demonstrated by annual sulphur dioxide emissions which ranged from 496,000 tonnes to 1,474,000 tonnes during the study period.

The major findings from the studies performed are:

- In order of emission magnitude (Table 7.1), the most significant source in the Sudbury Basin is the 381 m stack at the Inco Metals Copper Cliff smelter which contributes anywhere from 50% to over 80% of all emissions in the Basin. The other sources in the area are the Inco 194 m IORP stack, the Falconbridge 93 m smelter stack, and low level emissions from the Copper Cliff smelter building.

- The Sudbury environment is affected by contributions to total sulphate deposition from non-Sudbury sources, primarily due to long range transport. For example, Sudbury sources contribute on average, within a 40 km radius, about 10% of the total wet sulphate deposition in the Sudbury area. However, the Sudbury sources' contribution to dry deposition is highly direction oriented and quite significant, ranging from 30 to 70 percent of the total dry component.

- The deposition of trace metals from local sources is significant. Up to 70-80% of emissions of copper and nickel are deposited within the Sudbury area (40 km).

- Prior to 1972, significant acute and chronic injury to vegetation was recorded. This has been reduced to the extent that, presently, acute injury occurs infrequently, and is confined to relatively small, isolated areas and affects only those plant species most sensitive to sulphur dioxide. The greatest impact on soils in the immediate Sudbury area was concluded to have resulted from historical deposition of copper and nickel, which were often found in excessive levels. Their concentrations were found to decrease with increasing distance from the smelters.

- An estimated 200-400 lakes and 1,200 waterbodies of 10 hectares or less within 50 km of Sudbury are acidic (alkalinity less than 0 ueq l^{-1}). Many other lakes have been affected. Evidence indicates that a decrease in lake water sulphate levels can follow a reduction in sulphur dioxide emissions.

- A deposition rate of 39 kg SO_4^{2-}/ha·yr as listed for Muskoka-Haliburton (Table 5.1) is known to adversely affect the aquatic environment. Assuming that the contributions from all other sources remain unchanged, it is not possible to reach a deposition rate of 40 kg SO_4^{2-}/ha·yr in the Sudbury area even with a 100% reduction in local sulphur dioxide emissions.

- The evidence suggests that there should be a significant reduction in metal deposition in the Sudbury area of at least 90% for copper and nickel. The requirement for a reduction in metal loadings could be relaxed if acid loadings were to be reduced.

- The net downward trend in sulphur dioxide emissions, in conjunction with substantial liming efforts, have resulted in significant localized improvements in the terrestrial environment. In addition, some improvement has been realized in the lakes, but the current Sudbury emissions are still adversely affecting the local aquatic environment.

- The addition of neutralizing agents to the study lakes increased pH, provided residual alkalinity and decreased trace metal levels. However, biological communities typical of those in circumneutral lakes were not reestablished during the study period. Fish stocked in two of three neutralized lakes did not survive because water column trace metal levels remained too high after treatment.

2. INTRODUCTION

The Sudbury, Ontario environmental problem has drawn attention on a world-wide basis. (See Figure 2.1 for location of the study area.) The uniqueness of the Sudbury situation, which resulted from the impact of man's activities on the local environment over a period of 90 years, is without equal in scale.

This impact is best exemplified by the absence of vegetation and soil in the vicinity of the smelters at Copper Cliff, Falconbridge and Coniston. Not as apparent is the equally significant and extensive impact to the aquatic environment in the Sudbury area.

An appreciation for the causes of these effects can be gleaned by examining the history (1,2) of the mining and smelting activities in the Sudbury area. (See Section 3.) In the early years of mining activity (1888-1930), the ore was roasted in open heaps resulting in elevated ground level concentrations of sulphur dioxide (SO_2) gas adjacent to the heaps. It is estimated that approximately 28 million tons of ore were smelted between 1890 and 1930 and that this activity released approximately 11.2 million tons of SO_2 (1).

There is very little scientific evidence available to document the extent and severity of damage caused by the emissions from the roast yards, especially on the surrounding vegetation, although it is believed to have been considerable. Recent studies would indicate that the damage to the vegetation was due primarily to the SO_2 emissions as opposed to metal contamination. The practice of open roasting, which was largely responsible for damage to property and nuisance to residents, ceased in 1929 with the closure of the O'Donnell roast yard.

The problem of soil contamination by metals emitted from the smelters should not be viewed as the primary cause of the damage to the terrestrial ecosystem around Sudbury. Rather, the contamination occurred concurrently with a cycle where sulphur dioxide damaged the native vegetation which, in turn, was made more prone to forest fires. During that period (1883-1930), forest fires were very numerous in the Sudbury area. Any fresh growth of vegetation that developed following a fire was, in turn, subjected to sulphur dioxide fumigations. The sites, where vegetation was killed outright, became more vulnerable to erosion and subsequent soil removal from the hills. The loss of soil, plus metallic contamination of the remaining pockets of soil, made conditions very difficult for maintaining a vegetation cover on the rocky hills around Sudbury.

The net result was the creation of large areas of blackened rock and a landscape where trees and other vegetation were virtually absent. Severity of the damages was dictated by distance from the smelters, as well as by microclimatic conditions.

Less evident, but none-the-less equally significant, was the adverse effect these same activities were having on the Sudbury area aquatic environment. This impact required many decades to become apparent and it was not until the 1960's that studies (3, 4) fully documented the existence of abnormally low pH and high sulphate levels in many lakes, which were not directly affected by acidic mine tailings runoff, in the immediate vicinity of Sudbury. Additional scientific investigations (5, 6, 7) substantiated the widespread and serious nature of the adverse effects. Careful consideration of the data supported the premise that the observed changes in lake chemistry were a result of the interaction of atmospheric inputs and the widespread, relatively insoluble granitic bedrock common to the Sudbury area.

All these data collectively supported the conclusion that emissions from smelting operations, since the turn of the century, had contributed to the significant and severe detrimental environmental impacts in the Sudbury area. The consequences of over 90 years of mining and smelting activities can be summarized as follows:

- removal and perturbation of surficial soils in many areas;
- damaged, stunted and/or eliminated vegetative cover;
- many clear and fishless lakes;
- frequent, albeit seasonally dependent, fumigations.

Recognizing the need to better understand this environmental impact, the Government of Ontario initiated the Sudbury Environmental Study in 1973. The Study had the following objectives:

1. To determine whether or not the emissions from the Sudbury area mining operations were adversely impacting the local environment and, if so, to what degree;
2. To determine the extent to which the emissions should be limited in order to ensure that:
    a) the reclamation accomplishments to date are not reversed;
    b) no additional environmental damage due to the local sources ensues.

In order to meet the objectives of the Sudbury Environmental Study, research was undertaken in various study areas including atmospheric research, i.e. emissions, atmospheric processes, and modelling, as well as research related to terrestrial and aquatic effects.

This report presents a summary of these main areas of study, results of investigations carried out during the study, and conclusions derived from the study findings. In addition, a synoptic history of the impacts of emissions and measures taken to alleviate the environmental damage in the Sudbury area is presented.

Chapter 3, which outlines this historical perspective, illustrates the need for the study and provides background on the smelting companies involved and early government involvement. In addition, a history of SO_2 emissions in the area and their control is detailed. This Chapter also highlights the fact that, throughout the study period (i.e. from 1973 to 1980), the level of SO_2 emissions was not static but constantly changing due to increasingly restrictive SO_2 emission limits imposed by the Ontario Ministry of the Environment, as well as shutdowns in the operations of the two Companies either singly or collectively for various reasons (summer vacation, labour strikes), thereby complicating the interpretation of the study findings.

Chapter 5 provides a consolidation of the study results for total sulphur deposition. Chapter 6 describes the results of the various attempts to remedy the environmental damage to aquatic systems by the use of neutralization and fertilization techniques. Chapter 7 summarizes the conclusions reached based on the study findings.

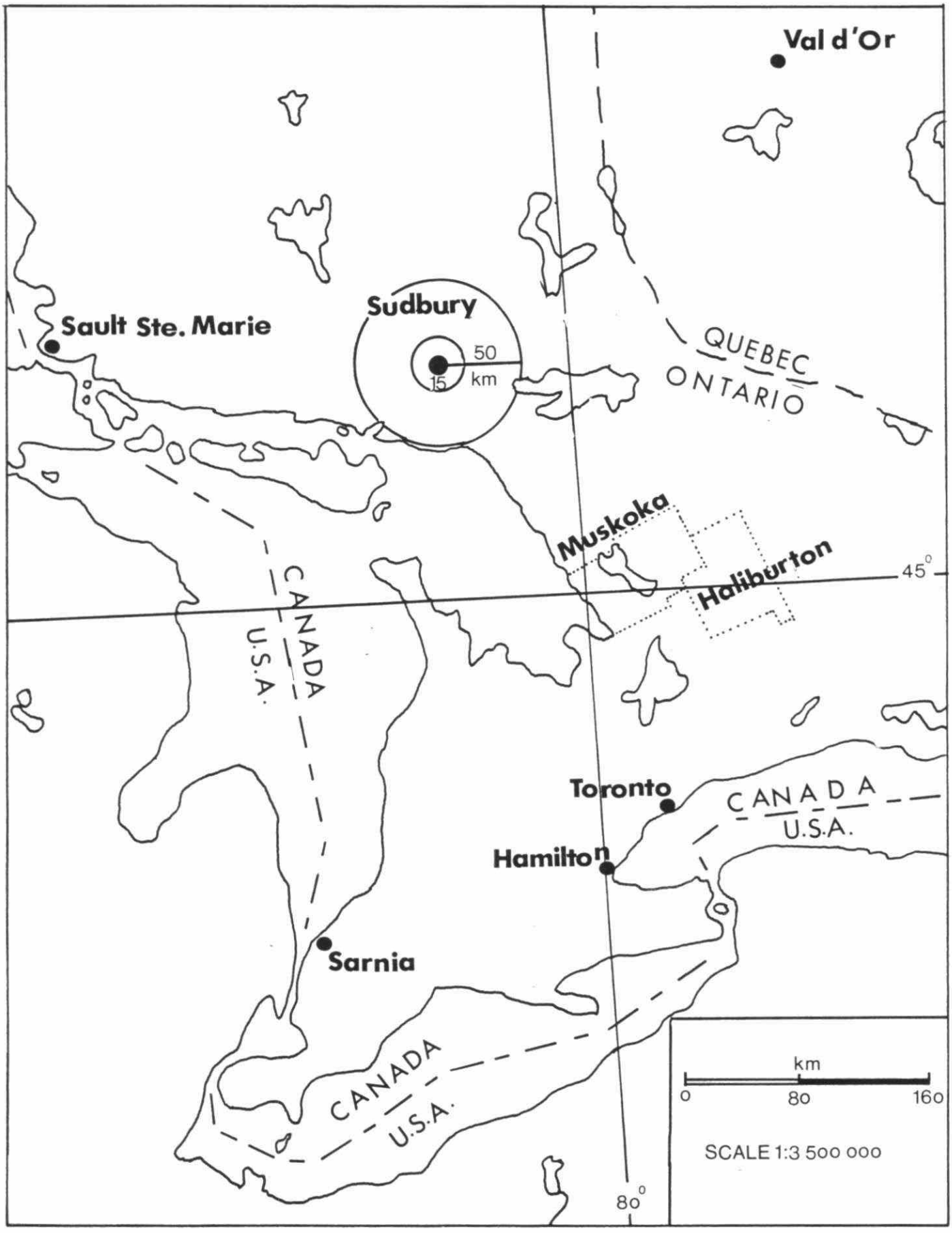

Figure 2.1. Location of the Sudbury Basin in Ontario

3. HISTORICAL PERSPECTIVE

3.1 The Environmental Problem

The primary historical problem has been due to SO_2 and its associated compounds. Over the years, elevated concentrations and deposition rates of these pollutants have seriously affected the Sudbury area biosphere. This adverse impact on the environment began with the commencement of ore roasting operations in 1888 and has continued to this day, albeit at significantly reduced levels from the 1950's and 1960's. In addition, the transport of these pollutants over long distances with the consequent impact on areas removed from Sudbury, has been recognized. Thus, the environmental problem is characterized by local and long range components. Over the intervening years, various process changes undertaken by the companies and abatement control programs imposed by provincial agencies have resulted in reductions in the emissions of SO_2 and other contaminants.

3.2 History of the Companies and Early Government Involvement

Although mineralized ore was discovered in Sudbury in 1883, it was not until 1888 that the first smelter was constructed at Copper Cliff (1).

Throughout Sudbury's mining history, over 100 companies initiated operations, but most either failed or amalgamated to form larger companies. Two of the early companies, the Canadian Copper Company and the Orford Copper Company, were united in 1903 to form the International Nickel Company. This Company was integrated with the Mond Nickel Company in 1929 to form the International Nickel Company of Canada.

By 1930, all smelter operations had ceased to exist except for those of the International Nickel Company of Canada located at Copper Cliff and at Coniston (smelter built in 1913).

Of all the companies that attempted to establish themselves in the nickel industry in the Sudbury area, only two persisted, namely Inco Limited and Falconbridge Limited. The current rated production capacities of the Inco and Falconbridge smelters are about 340 and 88 million pounds of nickel per year respectively.

With the growth of the mining industry around Sudbury came the growth of the city itself and the need for a service sector and a source of agricultural commodities. Concomitantly, the number of complaints from residents regarding damages and the nuisance of sulphur fumes also grew. To relieve the pressure from these complaints, the Canadian Copper Company and the Mond Nickel Company

petitioned the Minister of Mines to have certain lands withdrawn from further agricultural settlement. In 1915, an Order-in-Council was passed by which all patents, issued to settlers of land within the withdrawn area consisting of approximately twelve townships, had a clause exempting the mining companies from liability due to smoke damages.

As early as 1921, the Provincial Government introduced legislation (The Damages By Sulphur Fumes Arbitration Act, 1921) to facilitate the settlement of claims resulting from injury to vegetation by smelter fumes. This Act was repealed and replaced by The Damages By Sulphur Fumes Arbitration Act, 1924. The first Sulphur Fumes Arbitrator took office in 1925.

In 1944, the Sulphur Dioxide Committee, initially known as the Committee on the Investigation of Sulphur Smoke Conditions and Alleged Forest Damage in the Sudbury Region, was formed at the request of the Department of Lands and Forests with representatives from the Department of Lands and Forests, Department of Mines, the International Nickel Company, Falconbridge Nickel Mines, and other agencies acting in advisory capacities. The primary objectives of the Committee were to determine if sulphur dioxide and other smelter gases were causing injury to forest growth, and if so, over what area did this condition exist and what remedies could be applied.

The first SO_2 ambient concentration monitoring network was established in the Sudbury area in the mid 1940's. This permitted investigators to relate acute and chronic vegetation (forest) injury to measured ambient SO_2 levels and to determine the aerial extent of this impact.

The objectives of this Committee were only partly realized, and its work was terminated in 1972, at which time the bulk of the activities were taken over by the Ministry of the Environment.

Therefore, it appears that the early role of provincial agencies in dealing with this environmental problem was to arbitrate the settlement of damage claims from the public and to investigate the problem in order to determine the extent of the damage and to identify the remedial measures required.

3.3 History of SO_2 Emissions and Their Control

3.3.1 Control Programs Prior To 1969

The first attempt at effecting some control of SO_2 emissions comprised the relocation of roast yards further away from populated areas. Concurrently, smelters were built, which lessened the roasting requirements from the roast yards to the extent that in 1929 all open roasting activities in the Sudbury area ceased. These smelters

dispersed SO_2 emissions through stacks which were built progressively taller, such that by the mid 1930's the Inco Copper Cliff smelter had commissioned stacks with a height of 106 and 152 meters. Today, the Inco Copper Cliff smelter and Iron Ore Recovery Plant disperse SO_2 emissions to the atmosphere through a 381 m and 194 m stack respectively. The Falconbridge smelter disperses its SO_2 emissions through a 93 m stack.

A summary of the historical annual SO_2 emissions from the Inco Metals Company and Falconbridge Limited smelting operations is presented in Table 3.1. The emission figures were calculated on a calendar day basis from the total annual emissions computed by mass balance and provided by the companies. The emission rates in parentheses were calculated on an operating day basis for the years when production was curtailed as a result of labour strikes or shutdowns due to the reduced market demand for nickel and copper.

3.3.1.1 Inco Limited

Prior to the issuance of the first Control Order on Inco Limited in 1970 to control SO_2 emissions from its Sudbury operations, the Company implemented a number of programs which resulted in a gradual increase in the degree of sulphur containment. These programs, however, were largely oriented at increasing production capacity in a cost effective manner. They comprised pyrrhotite rejection, liquid SO_2 production and sulphuric acid manufacture. These sulphur containment practices resulted in an overall increase in SO_2 containment from about 20% (sulphur contained/sulphur in ore) in 1955 to about 30% in 1969 (8). A chronological summary of these programs is presented in Table 3.2.

On the basis of the emissions data presented earlier in Table 3.1, up to about 1969, daily SO_2 emission rates ranged from about 4500 tonnes to about 6200 tonnes. This wide range is believed to reflect variations in production rates and the implementation of the programs listed above including the commissioning of the Iron Ore Recovery Plant (IORP) in 1956.

3.3.1.2 Falconbridge Limited

Prior to the issuance of the first Control Order on Falconbridge Limited in 1969 to reduce SO_2 emissions from its smelting operations at Falconbridge, the Company reduced its overall emissions largely through pyrrhotite separation and rejection. This sulphur containment practice effected reductions in SO_2 emissions to the atmosphere on a nickel production basis. In 1940, 7.8 tonnes of sulphur were emitted per tonne of nickel produced, whereas in 1970, 5.2 tonnes of sulphur were emitted per tonne of nickel produced,

resulting in a 33% improvement in sulphur containment expressed on the basis of nickel production (9). However, the overall SO_2 emissions to the atmosphere were higher in the 1950's and 1960's, compared to those in the 1940's (see Table 3.1), due to increasing production levels and the commissioning of the pyrrhotite treatment plant in 1953. In the mid 1960's, the Company undertook the pilot plant development and economic evaluation of a process to convert SO_2 roaster off-gas to elemental sulphur. At that time, there were expectations that about 90% of the sulphur present in roaster off-gases would be recovered, thereby effecting significant reductions in overall SO_2 emissions to the atmosphere. Unfortunately this process did not prove to be viable.

3.3.2 Control Programs Since 1969

3.3.2.1 Inco Limited

In July 1970, the first Control Order was issued to Inco Limited to control SO_2 emissions from its Sudbury operations. This control program required the following:

a) construction of a 381 m stack at the Copper Cliff smelter by December 31, 1971;

b) reduction in SO_2 emissions at the Copper Cliff smelter in a step-wise fashion as shown below:

Date	Daily Emission Limit (tons)	Daily Emission Limit (tonnes)
July 1, 1970	5200	4716
December 31, 1974	4400	3990
December 31, 1976	3600	3265
December 31, 1978	750	680

c) reduction in SO_2 emissions at the Iron Ore Recovery Plant to 250 tons (227 tonnes) per day by December 31, 1972 by increasing acid plant capacity;

d) reduction in SO_2 emissions at the Coniston smelter to 60 tons (54 tonnes) per day by December 31, 1978;

e) cessation of the use of the three existing chimneys at the Copper Cliff smelter by December 31, 1971.

Throughout the negotiations which culminated in the above control program, it was repeatedly stressed that the construction of the 381 m stack was to be only an interim measure in the overall program. The reduction in

overall emissions at the smelter to 750 tons (680 tonnes) per day by December 31, 1978 was expected to be achieved by the application of a new hydrometallurgical process for treatment of Sudbury nickel concentrates (resulting in an overall SO_2 emission level of 1000 tons (907 tonnes) per day by 1978) and control of the copper converter gases assuming an 80% collection efficiency (amounting to an additional decrease of about 250 tons (227 tonnes) per day). The overall cost of this program was estimated to be $476 million dollars based on 1970 dollars.

In 1971, the Company informed the Ministry that its plans for a control program had changed due to the increase in operating and capital costs (excessive capital and royalty payments for the hydrometallurgical process), together with the bleak outlook for the sale of sulphur. As a result, that year the Company submitted a new program to meet the terms of the Minister's Order to the end of 1974, and cancelled its second major IORP expansion project because of escalating costs and lack of sulphuric acid markets.

The 1970 Minister's Order was amended in 1972, thereby granting an extension for the completion date of the 381 m stack and cessation of the use of the three existing chimneys at the Copper Cliff smelter to August 31, 1972. This extension was required due to construction delays. The SO_2 emission limits for the Iron Ore Recovery Plant and the Copper Cliff smelter remained unchanged.

In April of 1972, the Company shut down its Coniston smelter while in August it commissioned the new 381 m stack (with additional gas cleaning equipment) at its Copper Cliff smelter. That year, the Company built a new mineral dressing test centre, primarily for studies on pyrrhotite separation and rejection.

The 1972 Amending Control Order was amended in January 1973. Submissions were made by the Company in 1972 to change the schedule of SO_2 emission limits; the Company advised the Ministry that the hydrometallurgical process for the treatment of Sudbury nickel concentrates was completely out of the question due to capital costs and concerns regarding its applicability to Sudbury ores. However, changes to the control program were only allowed for the IORP control program. The major requirements of the 1973 Amending Control Order were as follows:

i) to continue to desist from using the three existing chimneys located at the Copper Cliff smelter;
ii) to limit emissions of sulphur dioxide from the Iron Ore Recovery Plant so as not to exceed 650 tons (590 tonnes) per day for the periods January 1, 1973 to April 15, 1973, and October 16, 1973 to April 15, 1974, and not to exceed 250 tons (227 tonnes) per day for the period

April 16, 1973 to October 15, 1973. Further, total emissions from that plant were not to exceed 250 tons (227 tonnes) per day after April 16, 1974;

iii) the schedule of SO_2 emission limits for the Copper Cliff smelter remained unchanged from the 1970 Minister's Order;

iv) the emissions of sulphur dioxide from the Company's smelter in Coniston were not to exceed 60 tons (54 tonnes) per day after December 31, 1978. (The smelter was shut down in April, 1972.)

In 1973, the Company voluntarily adopted an emission reduction program to improve Sudbury area ambient air quality by meteorological forecasting and reducing smelter operations during periods unfavourable for atmospheric dispersion.

In 1974, the IORP acid plant was expanded to increase its capacity to about 3000 tons (2721 tonnes) per day. The Company was able to comply with the 1974 limit on SO_2 emissions from the smelter.

During the period 1973 to 1976, the Ministry met with the Company on a number of occasions to discuss the status of the control program and submissions made by the Company.

In the summer of 1976, the Company submitted a control program proposal. The emission level requested amounted to 3100 tons (2812 tonnes) per day of sulphur dioxide or 32% of the sulphur mined. This proposed control program was estimated to cost $160 million and was scheduled for completion by the end of 1980. In addition, the Company requested permission to emit 3800 tons (3447 tonnes) per day of sulphur dioxide until the end of 1980. In the fall, the Ministry met with the Company to discuss this new submission. The Order was not changed at that time and the Company did comply with the 3600 tons (3265 tonnes) per day limit required by December 31, 1976.

During the period from 1975 to 1977 the Company spent over $23 million on preliminary programs related to nickel flash furnace technology and acid plants with respect to their feasibility for implementation at the Sudbury operations.

It became apparent that the 750 tons (680 tonnes) per day emission limit for the smelter as required by the 1970 Order would not be met, since the proposed technology for the process change being considered to attain the emission level reduction was not feasible.

In July of 1978, a new Control Order and a Provincial Officer's Requirement under the Environmental Protection Act 1971, and a Requirement and Direction under the Water Resources Act were issued to Inco Limited. The Control Order required that sulphur dioxide emissions from the

Copper Cliff smelter be limited to 3600 tons (3265 tonnes) per day and required control of operations at both the Iron Ore Recovery Plant and Copper Cliff smelter to ensure compliance with specified ground level SO_2 concentrations. This Order was to expire on June 30, 1982.

The rationale for the extension in time of the emission limit of 3600 tons (3265 tonnes) per day from the smelter was largely based on the fact that, by the end of 1977, the extent and severity of the acid rain problem was becoming more apparent, and that information on metal content of rainfall was becoming available, highlighting a further potential problem. It became evident that from an environmental point of view, any control program developed for the Inco smelter had to be evaluated in light of a number of potential environmental implications. This situation was further complicated by a lack of hard scientific data to clearly define the extent and nature of these environmental problems, thereby not allowing for possible correctivemeasures to be defined. Therefore, it was judged best to await the results of the Sudbury Environmental Study, established by the Ministry in 1973 to provide the scientific data necessary to determine the magnitude of SO_2 emission reductions required to achieve environmentally acceptable levels, before mandating further emission reductions.

In September of 1980, an Amendment to the July 1978 Control Order was issued. At the same time, Regulation 301/80, which required the Company to limit sulphur dioxide emissions from the Copper Cliff smelter to less than 2500 tons (2268 tonnes) per working day immediately, with a reduction to 1950 tons (1769 tonnes) per working day by 1983, was passed.

The basis for these new requirements developed after 1978, as a result of preliminary quantification of the potential environmental implications associated with the operation of the Copper Cliff smelter. It was believed that action needed to be taken to reduce emissions of sulphur dioxide from the smelter to minimize environmental problems associated with possible production increases. It was recognized by the Ministry that the steps in this proposed program would not totally solve local or continental environmental problems but that they would form a basis for further control requirements as additional data became available.

In summary, the Company was able to meet the control requirements as specified by the Ministry except for the last step, which required a reduction of sulphur dioxide emissions from the Copper Cliff smelter from 3600 tons (3265 tonnes) per day to 750 tons (680 tonnes) per day, by: a) closing the Coniston smelter, b) building additional acid plant capacity at the Iron Ore Recovery Plant c) building the Clarabelle concentrator, and d) modifying the old Copper

Cliff concentrator for more efficient pyrrhotite removal. In so doing, the Company improved its overall sulphur dioxide containment (expressed as sulphur contained/sulphur in ore) from about 30% in the late 1960's to about 70% in the late 1970's (8).

3.3.2.2 Falconbridge Limited

The first Control Order to limit sulphur dioxide emissions from the Falconbridge smelter operations was issued to Falconbridge Limited in November, 1969. This control program required a 55% reduction in SO_2 emissions by December 31, 1975 (from 1028 tons (932 tonnes) per day in 1969 to 465 tons (422 tonnes) per day in 1975) on an annualized average basis. At that time, the Company was planning to meet these requirements by a combination of the following:

a) the commissioning of a nickel-iron refinery with elemental sulphur recovery (Falconbridge Limited had initiated a study of this process in the mid 1960's in conjunction with Allied Chemical Canada Limited);

b) the adaptation of a roasting-briquetting process to provide strong gases for sulphur recovery, thus allowing the continuation of blast furnace smelting; and,

c) in the longer term, the research and development of a suitable hydrometallurgical process.

Unfortunately, neither the nickel-iron refinery process (shut down in 1972) nor the blast furnace smelting of roast-briquetting product proved to be viable. Further, since the hydrometallurgical process approach was only being considered for the longer term, this emission reduction program was unavailable for meeting the Control Order requirements.

Due to the infeasibility of these process changes, Falconbridge Limited requested, and was granted, an extension in its control program with a new Control Order being issued in 1973. This new control program required that:

a) by December 31, 1976, the operation of one half of the existing sinter plant, i.e. three machines, be replaced by a fluid bed roaster;

b) by December 31, 1976, the sulphur dioxide emitted from the fluid bed roaster be treated in a sulphur recovery plant;

c) by December 31, 1976, one blast furnace be replaced by an electric furnace;

In addition, the Company was required to take steps so that:

a) by May 31, 1979, the remainder of the sinter plant be replaced by a fluid bed roaster;

b) by May 31, 1979, the sulphur dioxide emitted from the fluid bed roasters be treated in a sulphur recovery plant;

c) by May 31, 1979, the remaining blast furnace be replaced by an electric furnace.

Further, the following new sulphur dioxide emission schedule for the Falconbridge complex was detailed:

Date	Daily Emission Limit	
	(tons)	(tonnes)
December 31, 1969	1028	932
July 1, 1973	850	771
December 31, 1976	660	599
May 31, 1979	465	422

Finally, the Order required the Company to take further steps so that by December 31, 1980, the emissions of sulphur dioxide from the Falconbridge complex would not, in the aggregate, result in a concentration at a point of impingement greater than 0.3 parts per million (830 ug m^{-3}) averaged over a thirty minute period.

Design of this new smelting process, as required by the control program, was initiated in the spring of 1973. In August of 1974, approval was given by the Board of Directors of the Company for the $95 million capital expenditure required for the project. The process that evolved from the studies conducted by Falconbridge Limited was a two-line fluid bed roasting-electric furnace smelting system with a single sulphuric acid plant to treat roaster off-gases from both lines.

Due to a lengthy strike and adverse economic conditions, activity on the smelter project was suspended in August, 1975 and not reactivated until the end of July, 1976. In December, 1976, the Company applied for a further extension for compliance on the grounds that economic restraints together with a revised construction schedule made it necessary and reasonable to do so.

An Amending Control Order was issued in July, 1977 which provided for the Company's request. This revised control program required the Company, by May 31, 1979, to:

a) complete the installation of the two fluid bed roasters and the two electric furnaces;

b) cease the operation of the six sinter machines and the two blast furnaces;

c) direct sulphur dioxide from the fluid bed roasters to the acid plant.

These abatement activities would enable the Company to comply with the revised SO_2 emission schedule contained in that Order:

Period	Maximum Number of Tons Per Day Averaged Over the Period
January 1, 1977 - December 31, 1977	850 (771 tonnes)
January 1, 1978 - December 31, 1978	850 (771 tonnes)
January 1, 1979 - May 31, 1979	850 (771 tonnes)
June 1, 1979 - December 31, 1979	465 (422 tonnes)
Each succeeding calendar year	465 (422 tonnes)

The 1977 Amending Control Order also required the Company to:

a) submit to the Director of the Northeastern Region a study by December 31, 1980, together with preliminary plans, outlining the methods by which emissions of sulphur dioxide from the smelter complex would be reduced to comply in the aggregate with the standard prescribed in Schedule 1 of Regulation 15 under the Environmental Protection Act, 1971;

b) reduce emissions of sulphur dioxide from the smelter complex by December 31, 1983, so that in the aggregate they comply with the standard prescribed in Schedule 1 of Regulation 15 under The Environmental Protection Act, 1971.

In essence, under the revised program, Falconbridge Limited constructed both smelting lines at the same time instead of sequentially as originally proposed.

The first line electric furnace smelting process (with acid plant) was started up in May 1978, along with the continued operation of the blast furnace smelting operation until July of 1978, at which time the smelter was shut down for summer vacation. Following summer vacation, the one line smelter operated alone, i.e the old smelter operation was discontinued, almost one year ahead of Order requirements.

Pyrrhotite roasting on the second line to produce market sulphuric acid commenced in September of 1978 and continued until November of 1979.

The second line of the smelter was prepared for the treatment of concentrate for early 1980 and both lines are currently operating on a copper-nickel concentrate producing matte and sulphuric acid while maintaining emissions below 465 tons per day.

In summary, the Company was unable to meet the schedule of the initial control program laid out in 1969 due to the failure of the new process technology that would have ensured compliance. However, it was able to meet the overall SO_2 emission requirements of the control program (emission target of 465 tons (422 tonnes) per day) largely due to the installation of a new smelting process with sulphur fixation as sulphuric acid, and to a lesser degree, through more efficient separation and rejection of pyrrhotite. In so doing, the Company improved its overall sulphur dioxide containment (expressed as sulphur contained/sulphur in ore) from about 17% in 1953 to about 84% in 1980. These figures include the sulphur present in the matte which is refined in Norway, and amounts to about 5% of the sulphur contained to the sulphur in the ore.

3.4 Current Status

3.4.1 Inco Limited

The control program presently in effect for Inco Limited (1980 Control Order and Regulation 301/80) requires the Company to emit no more than 2500 tons (2268 tonnes) per working day from the Copper Cliff smelter complex (under Regulation 301/80) averaged over twelve month periods ending at each calendar quarter. This emission level is to be met, over a twelve month period, up to the period ending at the end of the third quarter of 1983, that is up to and including the period October 1, 1982, to September 30, 1983. Thereafter, emissions during each twelve month period, ending at the end of the fourth calendar quarter of 1983 (i.e. January 1, 1983 to December 31, 1983) and ending at each calendar quarter thereafter, shall not exceed, in the average, 1950 tons (1769 tonnes) per working day.

SO_2 emissions from the Iron Ore Recovery Plant, as required by the 1980 Control Order, cannot exceed 250 tons (227 tonnes) per working day. In addition to these restrictions on total SO_2 emissions, the Copper Cliff smelter complex and the Iron Ore Recovery Plant require control of their operations to ensure compliance with specified SO_2 ground level concentrations (0.25 ppm hourly average for emissions from the Iron Ore Recovery Plant complex alone; 0.50 ppm hourly average for emissions from the Copper Cliff smelter complex either alone or in combination with emissions from the Iron Ore Recovery Plant complex). To date, the Company has been able to comply with these SO_2 emission limits (see Table 3.1) largely as a result of reduced production levels in light of poor metal market conditions. The 1950 tons (1769 tonnes) per working day emission level for the Copper Cliff smelter complex will be met with additional pyrrhotite rejection at the Copper Cliff mill.

3.4.2 Falconbridge Limited

To date, Falconbridge Limited has been in compliance with the control program presently in effect (1977 Amending Control Order). One of the requirements of this Order is for the Company to reduce emissions of SO_2 from the Falconbridge smelter complex by December 31, 1983, so that, in the aggregate, they comply with the standards prescribed in Schedule 1 of Regulation 15 under The Environmental Protection Act, 1971. This standard for SO_2 is 0.3 ppm (830 ug m^{-3}) concentration at point of impingement for a half hour average.

As required by this Amending Control Order, the Company submitted a report in December 1980 describing its proposal to reduce emissions to comply with this SO_2 standard. At a meeting with the Ministry in the spring of 1981, Company representatives advised that a further reduction in SO_2 emissions could not be effected by December 31, 1983 to comply with the final requirement of the 1977 Amending Control Order. The Ministry was further advised that the Company had undertaken a metallurgical research and development program with the aim of further reducing SO_2 emissions from the Falconbridge smelter complex. This research program involves higher degrees of roasting in the fluid bed roasters, slag cleaning, SO_2 absorption from dilute gas streams, a converter gas study and an acid plant capacity study. In addition the feasibility of adopting an intermittent emissions reduction program analogous to the one used by Inco Limited will be investigated. The Company estimates that this research program will cost over $5 million and may be completed by the end of 1984.

Table 3.1.

Sulphur dioxide emissions from the Inco Limited and Falconbridge Limited operations in the Sudbury Basin

YEAR	SULPHUR DIOXIDE EMISSIONS (Tonnes Per Calendar Day)* INCO	FALCONBRIDGE
1940	4647	278
1950	4766	462
1955	5024	
1956	5614	800
1957	5837	
1958	3508 (4707)	780
1959	5673	
1960	6218	816
1961	6086	
1962	4893	756
1963	4582	
1964	5129	646
1965	6166	
1966 (strike year - Inco)	5104 (5447)	790
1967	5711	813
1968	5755	935
1969 (strike year - Inco and Falconbridge)	3589 (5552)	651 (880)
1970	5454	929
1971	5118	992
1972 **	4162 (4416)	885 (915)
1973 ***	3249 (3448)	751
1974	3331	707
1975 (strike year - Inco and Falconbridge)	3282 (3385)	534 (668)
1976 +	3340	523 (560)
1977 +	3115	548 (619)
1978 +(strike year - Inco)	1553 (2613)	321 (374)++
1979 +(strike year - Inco)	1118 (1933)	241 (251)
1980 +	2225	337 (351)
1981 **	1981 (2146)	312 (334)

* Tonnes per operating day within parentheses. For the other years, the smelters were operating every day of the year.
** Summer vacation shutdown (Inco and Falconbridge).
*** Summer vacation shutdown (Inco).
\+ Production shutdown (Falconbridge).
++ New Smelting process implemented that year.

Table 3.2.

Summary of Inco Limited programs related to sulphur containment

Year	Control of SO_2 Emissions
1946	First successful tests of separation of pyrrhotite by magnetic means.
1947	Laboratory tests on ammonia leaching of pyrrhotite showed promising results. Pilot plant tests undertaken on flash smelting of copper concentrates, 20 tons (18.1 tonnes) per day.
1949	Started pilot plant at Coniston, for the roasting and ammonia leaching of pyrrhotite.
1952	New 500 tons (454 tonnes) per day oxygen flash furnace and 375 tons (340 tonnes) per day oxygen plant commissioned at Copper Cliff. Commercial scale production of liquefied sulphur dioxide started by CIL at Copper Cliff.
1953	1000 tons (907 tonnes) per day copper flash furnace installed, replacing 500 tons (454 tonnes) per day unit. Commenced construction of first unit of Iron Ore Recovery Plant (IORP).
1955-56	Started operation of first two units of IORP, capacity 1000 tons (907 tonnes) per day of pyrrhotite, producing 260,000 tons (235,820 tonnes) per year of iron ore pellets.
1957-58	Pilot plant tests undertaken on production of elemental sulphur from SO_2 gas from the IORP, joint project with Texas Gulf Sulphur Corporation. (Now Kidd Creek Mines Ltd.)
1958	First acid plant commissioned at the IORP, capacity 400 tons (363 tonnes) per day.
1963	Completed first major expansion of IORP, capacity increased to 3000 tons (2721 tonnes) per day pyrrhotite, and 800,000 tons (725,600 tonnes) per year of iron ore pellets. Second acid plant commissioned at IORP, capacity increased to 1000 tons (907 tonnes) per day.
1967	Started construction of No. 1 fluid bed roaster on No. 1 reverberatory furnace to begin modernization of the Copper Cliff smelter and to produce a strong SO_2 gas for eventual recovery as sulphuric acid.

Table 3.2.

1967	Third acid plant commissioned at IORP raising acid capacity to 2500 tons (2268 tonnes) per day. Old acid plant at smelter shut down*; capacity replaced by IORP capacity. Started major expansion of IORP, intended to raise pyrrhotite treatment to 4500 tons (4082 tonnes) per day to produce 1,150,000 tons (1,043,050 tonnes) per year of iron ore pellets. Completion of construction of new Frood Stobie concentrator.
1968	Expanded copper flash furnace to 1500 tons (1361 tonnes) per day.
1969	Commissioned No. 1 fluid bed roaster at the Copper Cliff smelter.
1968-78	Over $14 million expended in research on hydrometallurgical treatment of nickel concentrate.
1969-71	Built Clarabelle concentrator and modified the old Copper Cliff concentrator for more efficient pyrrhotite separation.

* The old acid plant at the smelter produced acid with off-gases from copper converters (initially) and later also treated excess off-gas from the copper flash furnace.

4. REVIEW OF STUDIES CONDUCTED

In order to meet the objectives laid out for the Sudbury Environmental Study, it was essential to obtain information on the nature and quantity of smelter emissions, their dispersion, chemical transformation and ultimate deposition in the environment. A brief description of the studies conducted to provide that information is presented in this Section of the Report, together with an assessment of the impact of Sudbury emissions on local air quality and on local terrestrial and aquatic ecosystems.

4.1 Emissions

The major sources in the Sudbury Basin (see Figure 4.1) are located within 15 kilometers from the city of Sudbury, and are associated with two copper and nickel smelters, Inco Limited at Copper Cliff and Falconbridge Limited in the town of Falconbridge, and a nickel refinery - iron ore recovery plant complex (Inco Limited at Copper Cliff). These two sources account for almost all the sulphur dioxide and particulate matter emissions in the Basin. Details of these sources, such as the strengths and composition of their emissions, are given in a Ministry report (10).

Emissions of selected major pollutants from the measured sources in the Sudbury area are shown in Table 4.1. The most significant source of air pollution in the Sudbury Basin is the 381 m stack at the Inco Metals Copper Cliff smelter. Depending on the type of pollutant, this source may contribute anywhere from 50% to over 80% of all emissions in the Basin. The only exception is copper, which is emitted in comparable quantities from other sources as well. In order of emission magnitude, the other sources of significant pollution in the area are the Inco 194 m stack from its nickel refinery-iron ore recovery plant (IORP) complex, the Falconbridge 93 m stack and finally, the ventilators and windows in Inco's main smelter building at Copper Cliff which are sources of fugitive emissions.

The emissions of particulates, iron, nickel and copper from the Inco 381 m stack listed in Table 4.1 are considered the best estimates of yearly emissions. They were calculated from linear correlations between the measured emissions of sulphur dioxide and these species such that they correspond to annual sulphur dioxide emissions. Emissions from the other sources in Table 4.1 were measured in shorter periods and are in some cases based on the results of one test only.

About 78% of all sulphur dioxide and 77% of sulphuric acid emissions are exhausted from the Inco 381 m stack; for total particulates, the corresponding contribution from this source is 75%, while the contributions to metal emissions are from 37 to 55% except for lead and arsenic which are mostly emitted from this source.

Up to April 7, 1980, when the pellet plant associated with the iron ore recovery process was shut down, Inco's two 45 m stacks were significant sources of particulate and iron emissions in the Basin. The best available emissions data are based on a single testing campaign carried out on only one of the stacks. Hence, due to the paucity of data for this source, the emission rates presented in Table 4.1 were not included in the average emissions from the Sudbury Basin. This source is not expected to resume operation.

Emissions of oxides of nitrogen and hydrogen chloride were measured on two occasions at the Inco 381 m stack, and because they were small in comparison to sulphur dioxide and sulphuric acid, the measurements were discontinued at this and other stacks.

Particle size is an important parameter in understanding the deposition of particulate pollutants and in determining the airborne part of the particulate emissions. Since most of the sources in the Sudbury Basin are controlled and the majority of particulates is removed by electrostatic precipitation at the source, it is expected, and confirmed by testing that, a large percentage of the particulates is less than 10 microns (um) in diameter, which constitutes; to a large extent, suspended particulate matter.

4.1.1 Sulphur Dioxide

From Table 4.1, it can be observed that the yearly SO_2 emissions during the period 1973-1981 have been quite variable. This observation is supported by the data presented in Tables 3.1 and 4.2. In the case of Inco Limited, a nine-month strike from early fall of 1978 to late spring of 1979 was responsible for the major reduction in SO_2 emissions from its operations in those years. Reduced levels of production and more stringent emission controls by the Ministry account for the level of emissions during 1980 and 1981. In the case of Falconbridge Limited, reduced production levels and more stringent emission controls are responsible for the gradual decrease in emissions. In 1978, the Company put into operation a new fluid bed roaster-electric furnace smelting process, together with a sulphuric acid plant. This resulted in increased sulphur containment and reduced SO_2 emission levels.

It is important to stress that the variable nature of the SO_2 emissions during the life of the Sudbury Environmental Study provided an additional complexing parameter to otherwise state-of-the-art studies aimed at determining the impact of these emissions on the Sudbury environment.

4.1.2 Particulates

Most of the particulate emissions in the Sudbury Basin are from the Inco 381 m stack as shown in Tables 4.1 and 4.3, and average in excess of 11,000 tonnes per year during the period 1973 to 1981. The low level particulate emissions as shown in Table 4.3 were normalized with respect to production on the basis of data collected in 1978 and 1979.

From among individual smelting processes, the largest contributors to the low level particulate emissions from the Copper Cliff smelter are the copper converters which account for 64 to 70% of the total, followed by the nickel reverberatory furnaces accounting for 9 to 11%, the nickel converters also accounting for 9 to 11%, and finally, the copper flash furnace, for 3% of the total.

The Inco 194 m stack is the second largest industrial source of particulate emissions in the Basin. Emissions from the Inco 194 m stack have also been reduced since 1980, when additional precipitators were installed at the nickel refinery. However, the paucity of emissions data from the nickel refinery flue leading to the 194 m stack since the installation of additional precipitator capacity does not permit an accurate assessment of the degree of reduction effected. Nonetheless, it is believed that the reduction was substantial. Still, further testing is required for confirmation.

Particulate emission measurements in the Falconbridge smelter stack were performed in 1979 when the new smelting process was on line. Particulate emission levels of about 2.4 tonnes per day were obtained. Measurements conducted when the old smelting process was in use yielded higher emissions at about 19.2 tonnes per day.

4.1.3 Trace Metals

As shown in Tables 4.1 and 4.4, the largest source of nickel, lead and arsenic emissions is the Inco 381 m stack, followed by the Inco 194 m stack, the Falconbridge 93 m stack and the Copper Cliff smelter building. Prior to 1980, when additional precipitator capacity was installed at the nickel refinery, the 194 m stack used to emit almost as much copper and nickel as the 381 m stack. Another significant source of copper is Inco's Copper Cliff smelter building,

contributing about 37% of all copper emissions in the Basin. Iron was emitted in substantial amounts from Inco's two 45 m stacks until the pellet plant shut down in 1980.

The iron, copper and nickel emissions shown in Tables 4.1 and 4.4 were calculated from their correlation with sulphur dioxide emissions, while lead and arsenic emissions were averaged from three or more valid emission measurement tests.

The Inco 381 m stack is the only emission point of trace metals in the Sudbury Basin for which annual emissions data are available since this source was extensively studied. Average emissions of five major metals from this source in kg/hour are presented in Table 4.5.

The average emissions of most of these trace metals and total particulates appear to have decreased as of 1978, presumably due to lower production levels. The comments made previously with respect to the dynamic nature of smelter emissions in relation to the environmental studies conducted in the Sudbury area are also of relevance for these emissions.

Emission rates of a number of other trace metals from the Inco and Falconbridge facilities are presented in a Ministry report (10). This is approximately 1% of the amount of SO_2 emitted over the same period.

4.1.4 Sulphuric Acid

The largest emission point of sulphuric acid is the 381 m stack (see Table 4.1) with an average emission rate of 7,270 tonnes per year for the period 1973 to 1981, followed by the 194 m stack, the Falconbridge 93 m stack and low level Copper Cliff smelter emissions. On average, 9,420 tonnes per year of sulphuric acid were collectively emitted from these sources during that period. This is approximately 1% of the amount of SO_2 emitted over the same period.

4.1.5 In-Plume Measurements of Emission Rate and Particle Size Distribution

In addition to in-stack measurements, airborne studies were carried out in the Inco and Falconbridge stack plumes to determine the size distribution of various particulate constituents and their emission rates (11, 12, 13). These studies provided especially valuable information for the estimation of particulate deposition rates, since coarse particles (having diameters greater than 2.5 microns) are generally deposited more rapidly than fine particles (with diameters less than 2.5 microns). Iron, copper and nickel were generally found to be in the coarse particle category, while lead, zinc, arsenic, cadmium and sulphates were in the fine particle category.

4.2 Atmospheric Processes

4.2.1 Meteorology and Dispersion

4.2.1.1 Meteorology

The objectives of the meteorological program were to obtain long term information on atmospheric stability and wind speed (and hence, the capacity of the atmosphere to disperse smelter emissions), as well as to provide a meteorological data base for the development of mathematical models designed to assess the fate of locally emitted pollutants. Details of the meteorological measurement program are presented in a Ministry report (14).

The program consisted of the measurement of wind speed, wind direction and temperature in the vertical using a pilot-balloon minisonde system under fair weather conditions. During the last year of the program, total incoming solar radiation measurements were also made. Data analysis was focussed on characterizing the meteorology of the Sudbury area during summer months (May to September), because it is during this period that most of the plume impingement episodes (and hence, higher ground level concentrations and amounts of dry deposition) occur. The results of the meteorological measurement program are as follows:

- The mean mid-day mixing height for the months of May through September was found to be approximately 1000 m above ground level. The mixed layer height was relatively constant through June, July and August and was slightly lower in May and September. The maximum mid-day mixing height measured during the program was about 2328 m above ground level. The maximum for each month varied quite significantly. The greatest variability in mid-day mixing heights occurred in the months of May and June.

- Mean mixed layer winds in the period May to September showed a predominant wind speed of 4 to 6 m s^{-1}. Westerly component winds had a frequency roughly four times greater than easterly component winds, and wind speeds associated with the two components were noticeably different. For the period May to September, the average mixed layer speed for westerly component winds was 6.4 m s^{-1} while that for easterly component winds was 3.8 m s^{-1}. The differences in both the frequency and speed of the mixed layer winds have major implications on local air quality and dry deposition. The upper level inversion above the mixed layer capping inversion had a mean mid-day potential temperature lapse rate of 3.3° C km^{-1} over the study period.

The strong bias for westerly component mixed layer winds suggests that the dry deposition field for locally emitted pollutants should also be biased. Based on the wind direction frequency data, increased dry deposition would be expected in the northeasterly and easterly directions.

- Monthly mean values of total incoming solar radiation during mid-day hours (1100-1500 hours), averaged from May to September, were in the range of 600 to 800 W m^{-2}. Daily values over a monthly period were 200 to 500 W m^{-2} greater than monthly means. For days with known convective activity, the monthly means were 50 to 250 W m^{-2} greater than the mid-day means obtained using data from all days.

The results confirm field observations and evidence collected in the Sudbury area since 1972, in that tall stacks have limited effectiveness for eliminating elevated ground level SO_2 concentrations during convective periods, (mostly from May to September), due to frequent mid-day average mixing heights of about 1000 m or more above ground level.

4.2.1.2 Dispersion

In June 1978 and August 1979, intensive field studies were carried out in the Sudbury area to study the dispersion of the Inco 381 m stack plume in the convective boundary layer (CBL), and to provide experimental data for the verification of a short term-short range dispersion model for the estimation of ground level concentrations of SO_2 due to emissions from this stack. The results of this study are described in a Ministry report (15).

Airborne measurements were made of plume sulphur dioxide concentrations at various distances from this source. At the same time, ground level measurements were made of atmospheric turbulence as well as sulphur dioxide within the fumigation area, and minisondes were used to determine wind speed and direction as well as the vertical temperature profile.

It was confirmed during these studies that on warm, sunny days the Inco 381 m stack plume begins looping typically between 1000 and 1100 hours, with initial impingement at a distance of 10 km from the stack or less, resulting in intermittent ground level concentrations which can exceed 1 ppm (5-minute average). Farther downwind, the plume becomes well-mixed in the vertical, with lower and less intermittent concentrations.

4.2.2 Local Air Quality

4.2.2.1 Sulphur Dioxide

A Ministry report (16) published in 1978 showed that ground level SO_2 concentrations in the Sudbury area during the period 1967 to 1977 were substantially reduced after 1972. This improvement in air quality resulted from the commissioning of the 381 m stack, a decrease in overall SO_2 emissions from the Sudbury area smelters as of 1972 as well as from other major changes in smelting activities already discussed in Chapter 3.

SO_2 ground level concentration data collected since 1978 show that further improvements in air quality have been realized, as a result of imposed lower emission limits and of extensive production interruptions due to labour strikes and reduced demand for copper and nickel.

Improvements in the Sudbury area air quality since the early 1970's with respect to ambient SO_2 concentrations are best exemplified by the data from the Ash Street and Skead stations as shown in Table 4.6. The Ash Street station is located in the city of Sudbury, approximately 4 km NE of the Inco smelter; the Skead station is located about 20 km and 7 km NE of the Inco smelter and the Falconbridge smelter respectively, in a prevailing wind direction. Although the data in Table 4.6 show that substantial improvements have been realized during the 1970's, a considerable number of exceedances of the hourly criterion have occurred in recent years. During 1981, the Ministry of the Environment operated an SO_2 monitoring network which consisted of 15 stations. Out of a total of 121,192 hours monitored, 366 hours were recorded with average SO_2 concentrations above the hourly criterion of 0.25 ppm. (Of this total, 159 hours with average SO_2 levels greater than 0.25 ppm were measured at the Happy Valley station located about 2 km south of the Falconbridge smelter.) The annual criterion of 0.02 ppm has been consistently complied with as of 1976 and 1977 at the Ash Street and Skead monitoring sites respectively.

As of 1978, the 24-hour criterion of 0.10 ppm was exceeded on one occasion at the Ash Street station, whereas at the Skead station, the criterion has been exceeded about four to five times per year. Reductions in the frequency of exceedances of the short term (1-hour and 24-hour) SO_2 criteria at the monitoring stations located in and around the city of Sudbury since 1978 have resulted, in part, from a requirement for Inco Limited to operate an emissions reduction program for its 381 m smelter stack and its 194 m stack (IORP). This program requires the company to reduce SO_2 emissions during periods when elevated ground level concentrations of SO_2 are anticipated.

4.2.2.2 Total Suspended Particulates

The levels of total suspended particulates, measured with high volume air samplers, continue to be within the provincial criterion at all monitoring sites in the Sudbury area. The only exception occurred in 1980 at the Copper Cliff monitoring station when the criterion was marginally exceeded. Although the highest Ni levels in suspended particulate for the Sudbury area are measured at the Copper Cliff monitoring station (see Table 4.7), the 24-hour Ni criterion is only occasionally exceeded at that location. Substantial reductions in the average levels of Ni and Fe in suspended particulate have been noted at the Falconbridge monitoring station since the start-up of the new smelting process at the Falconbridge smelter.

During the 1978-1979 strike period, significant decreases of the average Ni and Cu levels in suspended particulate at all monitoring stations in the Sudbury area were observed; a similar but less significant trend was noted for Fe.

In summary, there is no doubt that substantial improvements in local air quality have been realized since the early 1970's as a result of government imposed abatement programs and reduced production levels. The annual and 24-hour SO_2 criteria have essentially been complied with at most monitoring locations. However, the desirable 1-hour SO_2 criterion continues to be exceeded, albeit at a reduced frequency, at most monitoring locations in the immediate Sudbury area (within about 20 km from the city).

4.2.3 Atmospheric Oxidation of SO_2

Atmospheric chemical transformations can have a significant effect on both the fate and the environmental impact of emitted pollutants. In the case of SO_2, complex and yet not fully understood atmospheric chemical reactions transform SO_2 molecules to sulphate (SO_4^{2-}) particulate matter by oxidation (combination with oxygen) in the atmosphere. The resultant sulphate particles can remain in suspension in the atmosphere for long periods of time and be transported long distances, but eventually reach the earth's surface through both wet and dry deposition processes.

The SO_2 to SO_4^{2-} oxidation rate in the Inco 381 m stack plume was studied in September 1974 and June 1975 (17). It was found that at distances close to the stack, sulphate accounts for 1.2 to 1.5% of the total sulphur and less than 10% of the total sulphur even as far as 100 km downwind from the source. The conversion rate ranged from 0 to 7% per hour with an average of 1% h^{-1}. There was some indication of a slight decrease in conversion rate in the plume farther away from the stack but no temperature or humidity dependence was observed.

Further investigations of the oxidation rate of SO_2 in the 381 m chimney plume were carried out by the Ministry in September 1976 and February, March and June, 1977 (18). It was found that particulate sulphur in the 381 m chimney plume appears to be predominantly in the form of sulphuric acid, and comprises less than about 4% of the total plume sulphur, out to distances of about 100 km from the Inco smelter.

These same investigations confirmed that the SO_2 oxidation rate in the Inco 381 m chimney plume is low, typically less than 0.5% hr^{-1}. This rate applies to temperature and relative humidity ranges of -11 to 18°C and 34 to 87% respectively and to plume ages less than about five hours. Estimates of the oxidation rate from the event precipitation chemistry network data (19) suggest that the above figure is also representative of "wet" conditions.

4.2.4 Removal and Deposition

Substances, whether in the gaseous or particulate form, emitted to the atmosphere eventually reach the earth's surface as a result of atmospheric deposition processes. Deposition values are usually expressed as the mass flux of material to the earth's surface in units of kilograms/hectare·year. If the deposition occurs as a result of scavenging by rain or snow, the deposition is termed "wet". In the absence of precipitation, deposition occurs through dry processes. Total deposition is the sum of the wet and dry contributions.

Wet deposition values can be obtained by using a collector which is open only during periods of precipitation, and then determining the concentration of substances in the precipitation samples. Bulk deposition measurements, which use a continuously open collector (as compared to one which is open only during precipitation periods), have also been used in the Sudbury Environmental Study to estimate atmospheric loading rates to lake basins. Bulk deposition includes both wet deposition and an (unknown) fraction of the particulate material which eventually reaches the earth's surface. In addition, measurements have been made on both an event and longer-term basis, as discussed below.

Direct measurement of atmospheric dry deposition is extremely difficult and no method presently exists that is suitable for routine field use. A commonly used approach is to measure the ambient ground level concentration of substances of interest and then to estimate the deposition flux from the product of the concentration and the "deposition velocity", although for most substances there are large uncertainties in the latter quantity.

The total sulphur deposition rate is commonly expressed as an equivalent sulphate deposition rate (kg SO_4^{2-}/ha·yr).

4.2.4.1 Air Resources Branch Deposition Monitoring Program

The Air Resources Branch of the Ministry implemented a monthly wet-only deposition monitoring network in mid-1978 in order to monitor long term (cumulative) wet deposition within a radius of about 150 km from Sudbury. In June of that year, an event wet deposition monitoring network was also installed, with sampling stations located within about 50 km of the Sudbury area smelters. This latter deposition network measured daily deposition on days with precipitation, such that most of the samples corresponded to precipitation events.

Both networks were operational until the end of the field program in May 1980. Details of the operation of these two networks and the monitoring results are given in Ministry reports (11, 19, 20).

In order to determine the dry deposition rates of various pollutants emitted by Sudbury area smelters, the Air Resources Branch set up a suspended particulate sampling network that operated from July 1978 to May 1980. Since the deposition velocity for particulates depends on their size, particle sizing measurements both at ground level and within the smelter plumes were also performed.

Additional details of the operation of this sampling program and the results of this study are given in Ministry reports (11, 21).

4.2.4.1.1 Cumulative Wet Deposition Sampling Results

It is of special interest that the Inco smelter (including the Iron Ore Recovery Plant) was not operating, either due to production shutdowns or labor disputes, during most of the first study year. The Falconbridge smelter was also shut down for a brief period (Falconbridge shutdown from July 1 to August 21, 1978; Inco shutdown from July 17 to August 27, 1978 and Inco strike from September 16, 1978 to June 7, 1979). Thus, a comparison of the two periods, June 1978 to May 1979 and June 1979 to May 1980, yielded information on the impact from the Inco smelter on long term wet deposition.

The results of this sampling program are as follows:

- During the lifetime of the operation of the network, the observed pH values ranged from 3.5 to 5.4, with a geometric mean of 4.1 for the entire network. The corresponding ranges and geometric means for concentrations of some of the other substances of interest are presented in Table 4.8.

- A comparison of the geometric means for the periods June 1978 to May 1979 and June 1979 to May 1980 gave the results in Table 4.9. These results suggest the importance of long range transport in view of the fact that a summer shutdown and an extensive labour strike at Inco took place during the June 1978 to May 1979 period.

- H_f (free hydrogen ions) are strongly correlated with H_t (total hydrogen ions). Strong acids accounted for, on average, 70% of the total acid content. H_f is better correlated with SO_4 than with NO_3. The correlation between NH_4 and SO_4 as well as NH_4 and NO_3 suggested that NH_4 is chemically associated with SO_4 and NO_3.

- The precipitation concentration and wet deposition fields for the 1978/79 and 1979/80 periods showed the greatest impact of smelting activities to be for copper and nickel. A second group of trace metals (lead, zinc, chromium and cadmium) showed only a minor smelter impact. Results for the other substances examined (H^+, $SO_4^=$, NO_3^-, NH_4^+, Fe, Al, Mg^{++}, Ca^{++}, K^+, Na^+ and Cl^-) apparently were largely governed by non-smelter-related phenomena, such as long range transport into the study area and contributions of local wind-blown dust or vehicular traffic.

Consequently, any increment in the cumulative monthly wet deposition rates due to Sudbury area smelters is evidently masked by the inherent variability in these long term data (due to precipitation variability, local contributions from non-smelter sources, and long range transport).

4.2.4.1.2 Event Wet Deposition Sampling Results

The objective of the event network was to quantify the relative contribution of the local smelter emissions from Inco and Falconbridge to precipitation quality and wet deposition of acids, major ions and trace metals in the Sudbury area. However, due to constraints of suitable sites and operators, the final network was designed primarily to assess the impact of the Inco source on the local environment.

An analysis of the impact of the Sudbury smelter emissions on the Sudbury area using data from approximately 180 rain and snow events during the period mid-1978 to mid-1980, with precipitation samples collected upwind and downwind of both Inco and Falconbridge, was carried out. The data were stratified according to the type of meteorological frontal passage, and whether or not the samples were influenced by the smelter plumes.

From that analysis, the following conclusions were made:

- The most acidic sample of the 2515 samples collected had a pH value of 3.4. The most alkaline one had a pH of 7.2. Most of the precipitation acidity can be attributed to H_2SO_4 and HNO_3. In this study, maximum SO_4 and NO_3 (as N) concentrations were 29.3 and 14.1 mg l^{-1}. Geometric mean SO_4 and NO_3 (as N) concentrations were respectively 2.8 and 0.5 mg l^{-1} suggesting that sulphuric acid is 1.6 times more important than nitric acid to precipitation acidity.

- Maximum concentrations (mg l^{-1}) of trace metals observed were: Fe = 3.9, Cu = 2.5, Ni = 0.9, Pb = 0.5, Zn = 1.7, Al = 2.3, Cr = 0.1, and Cd = 0.03. Most of the mean values were less than or equal to 0.01 mg l^{-1}.

- Precipitation concentrations associated with cold fronts were usually lower compared to those of warm fronts. Concentrations of the soil-derived constituents in winter precipitation were generally lower than those in summer precipitation.

- Precipitation concentrations of SO_4 were higher in the summertime, whereas those of NO_3 were higher in the wintertime. This observation may be a consequence of different emission conditions, and oxidation and scavenging properties of SO_x and NO_x in the two seasons.

- Precipitation concentrations of species such as H_f, SO_4, NO_3, and trace metals, which are found in the sub-micron particle size range and have contributions due to long range transport as well, were in general higher with trajectories from the S and SW sectors. This supports the observations that concentrations are higher during warm frontal passages than during cold ones.

- With the exception of copper and nickel, most of the wet deposition in the Sudbury area (within a radius of 40 km) can be attributed to sources other than the local smelters. Long range transport from sources to the south is implicated for many parameters, notably acidity and the acid-precursors, sulphate and nitrate, because significantly higher background precipitation concentrations occur in warm, rather than in cold, frontal storms. The former usually enter the study area from south of Sudbury.

- Nevertheless, a definite influence of the smelters on the local downwind precipitation quality can be detected for almost all of the substances known to be emitted, the contribution due to Inco being considerably larger than that due to Falconbridge, in qualitative agreement with their respective emission rates. For example, average downwind precipitation copper and nickel concentrations were found to be an order of magnitude higher than background values in Inco's case. In many cases, this smelter influence can be detected to a distance of more than 40 km from the source.

- Most particulate constituents (acid, sulphates, trace metals) are scavenged quite efficiently from the smelter emissions during both rain and snow storms, almost total removal occurring within the Sudbury area for some trace metals (e.g. copper). The percentage of the total emitted sulphur removed by precipitation is much lower, mainly because this sulphur is largely in the form of sulphur dioxide, which is subject to a low scavenging efficiency.

- During precipitation events, the Inco smelter contributes, on average, 70% of the total copper and nickel wet deposition within 40 km, and less than 20% of the total for other trace metals and sulphur.

Table 4.10 summarizes the results for wet deposition during precipitation events for some of the substances emitted by the Inco smelter. Information for Falconbridge is considered to be considerably less accurate, due to much poorer network coverage around the Falconbridge smelter, and possible interferences from the larger Inco smelter emissions and therefore, is not presented here.

In connection with the above results, two facts should be pointed out. Firstly, the smelter impact on deposition, listed in column 5 of Table 4.10, applies only to the level of smelter emissions (column 2) that occurred during the study period which was from mid-1978 to mid-1980. Any change in the emission rate is expected to cause a corresponding change in the smelter impact. Secondly, the percentage of smelter emissions removed (column 4) is computed only for periods when precipitation was actually occurring. These periods constitute about 10% of the total time, with various dry deposition processes providing the only removal pathway during periods without precipitation.

4.2.4.1.3 Dry Deposition Monitoring Results

The results reported here are based on the ambient concentration data for sulphur dioxide, particulate sulphate, nitrate and ammonium, and trace metals (Hi-Vol measurements) together with particle sizing measurements, both at ground level and within the Inco and Falconbridge smelter plume, of sulphate and various metals. A detailed meteorological analysis, together with ambient air concentration information, allowed a distinction to be made between samplers impacted by smelter emissions and those exposed to background air. The following conclusions were drawn:

- The geometric mean concentrations of the substances listed below, over the two years of operation of the sampling network, were:

Substance	Geometric Mean (ug m^{-3})
SO_2	12.7
SO_4^{2-}	2.6
NO_3^- (as N)	0.16
NH_4^+ (as N)	0.54
Fe	0.29
Ni	0.005
Pb	0.04
Zn	0.02
Cd	0.001
Al	0.10
Mn*	0.003
Mg*	0.73

* Limited data base available.

- Sulphur dioxide and sulphate correlated poorly, suggesting that the latter had a large contribution from long range transport. NH_4 and SO_4, however, did correlate well, suggesting that they were chemically associated.

- Ground level concentrations of most of the substances listed were found to be higher downwind of the Inco plume than the Falconbridge plume as expected from the relative source strengths. The parameters showing the greatest difference between plume and background concentrations were SO_2 and Ni.

- Dry deposition was determined to be a relatively inefficient removal mechanism for sulphur dioxide and substances predominantly in the submicron particle range (i.e. SO_4, Pb, Zn, Cd), with less than 5% of the emissions being deposited within 40 km of the smelter sources. On the other hand, a higher proportion of the coarse particles, containing most of the airborne Fe, Al and Ni (up to about 50% or more), were deposited within the same distance.

- During the study period, the smelter contribution to the total dry deposition within 40 km was greatest for sulphur (primarily due to SO_2) and nickel, making up 27% and 78% of the total respectively for Inco, and 23% and 40% for Falconbridge. The smelter contribution of the other metals examined (Fe, Pb, Zn, Cd and Al), was generally less than 20% of the total. Due to sampling problems, the corresponding figures could not be derived for copper, but results similar to those for nickel are expected, based on the available emission rate and particle size information.

Table 4.11 summarizes the results of the present investigation. It should be realized that the information on smelter impact on the dry deposition in the Sudbury area (i.e. the last column in the table) applies only to the level of emissions during the study period. Any change in emission rates is expected to cause a corresponding change in the smelter contribution.

It is extremely important to note that the wet and dry deposition rate results obtained from the Air Resources Branch program are average values within areas defined by radii of about 40 km from the Copper Cliff smelter (for wet event deposition) and from both the Copper Cliff and Falconbridge smelters (for dry deposition). At locations closer to these smelters, the local contribution to deposition per unit area, especially to total dry deposition, is higher than the average determined over the 40 km radius.

4.2.4.2 Water Resources Branch Deposition Monitoring Program

The Water Resources Branch of the Ministry performed bulk deposition rate measurements at eight locations within about 50 km from the city of Sudbury from 1976 to 1979. The precipitation collectors were located on or adjacent to the drainage basins and surfaces of the Sudbury Environmental Study Lakes (see Figure 4.1). The eight sampling sites were grouped into three stations (Sudbury North, 30 to 50 km north of Copper Cliff; Sudbury Center, 4 to 5 km south;

Sudbury South, 10 to 12 km south). Wet deposition was measured at Sudbury North and Sudbury Center only from May/June to October/November in the years 1977 to 1979. Both the bulk and the wet-only precipitation samples were collected when sufficient volume for analysis existed. Deposition was reported on a monthly basis. Information related to the operation of this deposition monitoring network and a detailed presentation of the results are given in Ministry reports (22, 23).

A summary of the composition of bulk deposition and wet-only precipitation samples is given in Table 4.12 for the entire study period. In this Table, ion concentrations are expressed on an equivalent basis (e.g. meq l^{-1}) to facilitate relative comparisons. Nutrient and metal parameters are expressed on a mass basis (mg l^{-1}).

The major results from the studies performed were the following:

- The high input of Cu, Ni, Zn and some of the Fe to the lakes in the immediate Sudbury area is principally due to direct atmospheric deposition. When the Inco Ltd. smelter and the iron ore recovery plant were not operating between September 1978 and April 1979, bulk deposition of Cu and Ni was reduced by almost two orders of magnitude to background levels similar to those measured at Muskoka-Haliburton, an area with no local source of metals.

- Mass balances for the calibrated watersheds demonstrated that 50% (at 30 km northwest of Copper Cliff) to 85% (4 km southwest) measured by the total deposition of strong acid was not measured by bulk collectors. The unmeasured input of acid was concluded to be the result of dry deposition of SO_2.

- The major cations in bulk deposition (on an equivalent basis) were H^+ Ca^{2+} Na^+ NH_4^+ Mg^{2+} K^+. The major anions were in the order SO_4^{2-} NO_3^- Cl^-.

- Deposition of materials in precipitation varied in time and in space. Deposition of H^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, TP, TKN and Zn was greatest during the summer when precipitation depth was greatest. Most of the annual Cu and Ni in bulk deposition occurred in the summer at Sudbury North, while Cu, Ni and Zn deposition was greatest in the winter at Sudbury Center and South. Deposition rates for SO_4, Cu, Ni and Fe decreased with increasing distance from the smelters.

- Deposition rates of Al, Mn, nutrients and major ions, excepting SO_4^{2-}, were similar or only slightly higher at the Sudbury stations than rates in south-central Ontario. However, deposition rates of Cu, Ni, Zn, Fe and SO_4^{2-}, were strongly influenced by local smelting activities. In fact, Cu and Ni deposition rates exceeded virtually all previously reported values for industrialized areas. Even at Sudbury North, the station with the lowest trace metal deposition rates, levels were 4-, 4- and 20-fold higher than in south-central Ontario for Zn, Ni and Cu, respectively (23).

- The ratio of wet to bulk deposition was greater than 50% for H^+, SO_4^{2-}, NO_3^--N, NH_4^+-N and Ni at Sudbury North and Sudbury Center, while the ratio of wet to bulk deposition was less than 50% for Na^+, Cl^-, TP, Fe, Cu and Zn. The ratio of wet to bulk was generally lower in Sudbury than in south-central Ontario which implies that the dry component of total deposition was generally more significant in Sudbury than in south-central Ontario.

- Sulphuric acid contributed approximately twice as much as nitric acid to the strong acidity bulk deposition at Sudbury, and was even more important when gaseous SO_2 inputs were considered. Seasonal variations in rates of SO_4^{2-} deposition did occur, resulting in relatively greater nitric acid contributions to total acidity in the winter. Even in the winter, however, nitric acid contributed less than 50% of the total strong acid inputs.

4.3 Modelling

Atmospheric dispersion models were developed by the Ministry in connection with the Sudbury Environmental Study to estimate, in the long term, the short range and long range contributions to the atmospheric deposition of substances emitted from Sudbury area smelters. The Ministry also developed a short range - short term fumigation model for the Inco 381 m stack in order to predict more accurately ground level concentrations of SO_2 resulting from emissions released in the convective boundary layer.

A detailed description of the long range - long term model and of the short range - short term model, together with results of model runs, have been given in Ministry reports (24, 25). Although the short range - long term model has been validated with measured SO_2 ground level concentration data in the Sudbury area, it is presently considered to be in the developmental stage. Further refinements are expected in calculations of both concentration and deposition. For these reasons, the

results of this model should be regarded as tentative. A Ministry report documenting the development of this model and providing results of model calculations for the Sudbury area is in preparation.

4.3.1 Short Range - Short Term Fumigation Model

Conventional "Gaussian type" dispersion models, based on the Pasquill-Gifford curves, do not accurately predict ground level concentrations of pollutants associated with plumes emitted into the convective boundary layer. A model was therefore developed for this purpose. The required data inputs to the model are: the climatology of the mixed layer height; solar radiation; mixed layer winds; and the temperature structure above the mixed layer. The model employs some of the most recent developments in the understanding of dispersion in the convective boundary layer.

Model predictions have been compared with SO_2 field data collected in Sudbury and elsewhere; the results of the comparison are very encouraging. The input parameters of this model depend on routinely available meteorological measurements. Hence, it is ideally suited for utilization in a supplementary emission control system. In this kind of application, the model could be used to predict the SO_2 emission rate which would ensure that the maximum expected concentrations would comply with Ministry requirements. Cutbacks in emissions could be implemented if an exceedance is predicted to occur.

4.3.2 Long Range - Long Term Model

A simple statistical model was developed to estimate the long range (greater than 150 km from the source) impact of sources on selected receptor areas. The model consists of three modules, namely, transport and dispersion, scavenging and atmospheric chemical processes. The model is formulated by determining the probability that pollutants released by a source at a given time would impact a receptor at a later time. Because of the statistical nature of this model, it is expected to perform well for long averaging times only (e.g. one year).

The model has been evaluated with annual wet sulphur deposition measurements at several receptors in the northeastern United States and in eastern Canada and is shown to predict wet sulphur deposition within a factor of two. An evaluation with ambient SO_4^{2-} concentration, again, resulted in an accuracy within a factor of two. It is not yet possible to evaluate models for dry deposition. Also, ambient SO_2 concentrations are affected by local sources, making it difficult for long range models to be evaluated for SO_2 concentrations. The dry deposition amounts, as predicted by the model, are expected to possess the same accuracy as the wet deposition amounts.

This model has been found useful for performing emission scenario studies. For instance, it may be desired to study the impact of the sources on selected receptors, specifically when these sources are reduced by a certain fraction. In that case, the model is executed with the reduced sources.

In this respect, four emission scenarios for the Sudbury area smelters were considered and are documented in Ministry reports (11, 24). The results of this exercise are summarized as follows:

- The model estimates show that sources in the Sudbury region (first scenario - actual 1977 emissions) contribute up to 30% of the total sulphur deposited during precipitation in most of central Ontario under typical mid-1970's SO_2 emission levels. Although Inco's emissions dominate the wet deposition contribution from Sudbury sources, Falconbridge does contribute a significant amount (up to 5% of the total).

- Sulphur dioxide emissions from the Sudbury area were greatly reduced by shutdowns and strikes during the 1978-1979 period (second scenario). The model estimates show a reduction in annual wet sulphur deposition of up to 20% of the total over approximately the same region of central Ontario.

- The third scenario (December 1980 SO_2 emission limits) represents the maximum contribution of current Sudbury emissions to the long term average deposition of sulphur, since actual annual emissions are expected to be somewhat less than the annual values calculated from maximum daily emissions. The model results show that the Sudbury region would contribute up to 25% of the deposition in central Ontario under these conditions.

- The results of the fourth simulation (current SO_2 emission limit of 465 tons (422 tonnes) per day for Falconbridge and of 1950 tons (1769 tonnes) per day for the Copper Cliff smelter) show that Sudbury emissions would contribute up to 23% of the total sulphur deposition during precipitation in central Ontario.

- In general, the model indicates that wet sulphur deposition in central Ontario receives a significant contribution from the smelters in Sudbury. Reducing emissions from Sudbury to the 1983 permissible level would significantly reduce this region's contribution to the total deposition of sulphur. The model also shows that, in spite of these reductions, Sudbury area emissions would still remain a major contributor to wet sulphur deposition in central Ontario.

4.3.3 Short Range–Long Term Model

The short range - long term model has been developed to simulate long term (annual or seasonal) average concentration and dry deposition of sulphur compounds at distances up to 100 km from the sources.

This model is based on the most recent understanding of dispersion under convective and stable conditions in the atmospheric mixed layer closest to the earth's surface. Model-computed values of SO_2 concentration in the air at ground level have been compared with measured concentrations at 17 monitoring sites in the Sudbury area for four specific summer and winter periods. Comparison shows that model values agree within a factor of two with measured values for 80% of the time.

Dry deposition is computed as the product of the ground level concentrations and the dry deposition velocity. In this model, the dry deposition velocity is derived as a function of wind speed, atmospheric stability, surface roughness and the resistance of soils and vegetation to the uptake of SO_2. The transfer of SO_2 to the ground has been observed to occur very slowly with low winds under stable conditions at night and over snow. This transfer is much faster with higher wind speeds during summer days when the air is turbulent and over woodlands and lush vegetation (21).

Preliminary estimates of dry SO_2 deposition in the Sudbury area using this model give the following results:

- Computed dry deposition due to Sudbury emissions shows a pattern which is roughly elliptical,with maximum values to the northeast and east and with minimum values to the northwest of Sudbury. In general, greater deposition rates prevail to the east than to the west. This is to be expected because of prevailing westerly winds.

- For the 12-month period June 1977 to May 1978, a total SO_2 dry deposition rate of 124 kg SO_4^{2-}/ha·yr was estimated for a receptor location 10 km northeast of the Inco 381 m stack. Of this total, the Sudbury contribution was estimated to be 105 kg SO_4^{2-}/ha·yr, while contributions transported to the Sudbury area from external sources were estimated to be about 19 kg SO_4^{2-}/ha·yr.

- Over the same time period, Sudbury contributions to total SO_2 dry deposition over the Clearwater and Nelson Lake areas were estimated to be about 49 and 14 kg SO_4^{2-}/ha·yr respectively. Total dry deposition, when the external contributions are included, are 68 and 33 kg SO_4^{2-}/ha·yr respectively.

These model estimates suggest that the local contributions to dry sulphur deposition in the Sudbury area constitute a significant fraction of the total sulphur deposition.

Additional dry deposition estimates for locations in the Sudbury area from this model will be presented in Chapter 5.

4.4 Effects

4.4.1 Terrestrial Effects

4.4.1.1 Vegetation: SO_2 Injury

The acute and chronic effects of SO_2 emissions on vegetation in the Sudbury area have been studied for some time and documented by a number of agencies and researchers (26-33). Observations of acute injury to vegetation (31, 32, 33) revealed that the most sensitive agricultural crops were buckwheat, barley and red clover, and that the most sensitive forest species were trembling aspen, bracken fern, white birch and white pine. Other studies (27, 28, 29) determined that eastern white pine forests exhibited both acute and chronic damage from atmospheric SO_2 up to a distance of 40 km northeast of Sudbury. This damage was measured in terms of foliage, bark and biological injuries, decreased radial and volume growth rates and tree mortality. Slight chronic injury was observed on eastern white pine trees at a distance of up to 65 km northeast of Sudbury.

Early work on acute vegetation injury, based on ground level SO_2 measurements using Thomas autometers, defined the boundaries of this type of injury. Short term, high concentration SO_2 fumigations were recognized as having the potential to cause injury to vegetation. Further, the effects of potentially injurious fumigations on vegetation were observed to depend, to a large extent, on the environmental conditions prevailing at the time of the fumigation and on the susceptibility of the vegetation to injury at that time, which is a function of season and relative humidity.

On the basis of observations of the extent of vegetation injury in areas adjacent to the sulphur dioxide monitoring stations, investigators found that injury could occur in response to the SO_2 doses as listed in Table 4.13.

These doses could be reduced by about 25 per cent, if environmental factors were especially conducive for acute injury to vegetation to occur (26). Conversely, injury would not develop in the presence of higher doses if the environmental factors were not conducive.

If vegetation were exposed, during daylight hours, to any of the doses listed in Table 4.13, then the fumigation intensity was assigned a value of 100 for convenience. If the fumigation intensity value was 100 or greater, then the fumigation was termed a potentially injurious fumigation (P.I.F.).

Using this information, the number of P.I.F.'s at each monitoring station could be determined. In Table 4.14 an account of the number of P.I.F.'s recorded at SO_2 monitoring stations in operation during the period 1965 to 1981 in the Sudbury area is presented. These data were taken from Ministry reports published in 1978 (16, 34) and from recent unpublished information obtained from the Ministry's SO_2 monitoring network.

Results of investigations conducted by the Ministry since 1970 demonstrate that abatement measures taken by both Inco Limited and Falconbridge Limited since 1972 to reduce total SO_2 emissions (see Table 3.1), to enhance the dispersion of these emissions (Inco 381 m. stack) and to curtail emissions during periods of poor atmospheric dispersion (Inco), have substantially reduced the number of P.I.F.'s as shown in Table 4.14. It is important to note that production shutdowns and/or labour strikes during some of the growing seasons also contributed to the reductions in the number of P.I.F.'s. The reduction has been substantial since the number of SO_2 monitors operated by the Ministry was increased progressively during the 1970's.

This marked reduction in the number of potentially injurious fumigations has resulted in a substantial decrease in the number of vegetation injury complaints diagnosed as SO_2 injury as shown in Table 4.15.

Whereas, in the years prior to 1972, acute injury to vegetation was occasionally observed as far away as 90 km from Sudbury, vegetation injury since 1972 has been reduced to the extent that acute injury has been confined to relatively small and isolated areas and has occurred only on plant species which are most sensitive to SO_2. Long-term chronic SO_2 injury as determined prior to 1972, was prominent in areas at a distance of up to 40 km northeast of Sudbury (Kukagami Lake) where the seasonal (May to October) average SO_2 concentration was about 0.017 ppm (44 ug/m^3). The types of chronic injuries to forest trees northeast of Sudbury included: accumulation of excess sulphur in perennial foliage; progressively increasing visible injuries to older foliage (tissue chlorosis and necrosis); premature loss of older foliage; reduced radial and volume growth of trees; and premature tree mortality (29).

4.4.1.2 Vegetation and Soil: Heavy Metal Contamination

Foliage samples of low sweet blueberry, red maple and wavy hair-grass collected at distances of up to 50 km along a transect from Inco's Coniston smelter (35) were found to have elevated concentrations of nickel and copper. For all three vegetation species, the levels of nickel, copper and iron decreased markedly with distance from the smelter.

Aluminum concentrations in foliage of wavy hair-grass suggested an impact from smelter emissions. Recent emissions results (10) indicate that aluminum is emitted in substantial quantities from both the Inco and Falconbridge smelters. However, a clear relationship with emissions could not be supported due to the very limited data base and also since soil pH controls the uptake of aluminum by plants.

This study (35) also revealed that the lowest soil pH values occurred in the surface soils, with pH increasing with increasing depth in the soil profile. The pH values of surface soils up to 7.4 km from the Coniston smelter, which was shut down permanently in 1972, were generally less than 3.0. (The pH of natural Canadian Shield podzolic soils is in the range of 3.5 to 4.5). Significant soil concentration/distance relations were observed for copper, nickel, cobalt, silver and iron, whereas no obvious pattern could be established for zinc, manganese, aluminum and vanadium. A marked soil-profile effect was shown for nickel, copper and cobalt, with the highest concentrations usually occurring in the surface soils. Soil distribution patterns for lead were less marked, whereas very little evidence of surface-soil loading for zinc and manganese could be found.

Field studies to determine the elemental composition of vegetation foliage samples were initiated during the 1970 growing season by the Ministry with the establishment of a number of permanent vegetation sampling plots in the territory affected by the Sudbury area smelters and a few control plots in areas remote from Sudbury. Concentrations of various chemical elements in plant species and soil at increasing distances from the smelters were first provided in a report prepared by the Ministry in 1973 (31). A summary of the results obtained over the period 1970 to 1976 is also available in a Ministry report (34).

In interpreting the results of this monitoring program, it should be noted that based on experience with numerous vegetation and soil sampling programs conducted throughout the Province, as well as on data published in the literature, a set of guidelines has been developed by the Ministry to indicate the concentrations of individual chemical elements which are considered to be excessive in plant tissue and in soil. "Excessive" does not necessarily

mean toxic, but is evidence of contamination above average normal levels. The excessive levels of contaminants in vegetation or soil are considered to be tools for use by phytotoxicology investigators in interpreting the results of chemical analyses. Certain limitations exist with these established levels and investigators must judge their use in supplementing other results and observations from field assessment surveys. The values used for that purpose are listed in Table 4.16.

The results of the 1970 to 1976 vegetation and soil sampling program are summarized as follows (34):

- Excessive concentrations of nickel and copper were frequently found in soil and vegetation samples collected at Sudbury, Garson and Skead, i.e. within about 20 km from the smelters. Excessive concentrations of these two metals were also found in some samples collected at slightly greater distances from the smelters (Rayside, Tilton Lake, Callum and Kukagami Lake). Most soil samples collected in the Sudbury study area contained elevated copper concentrations in relation to the control samples. A decline in the average concentration of sulphur in vegetation samples collected in the Sudbury area was observed in the period after 1972.

- A limited number of vegetation samples contained excessive levels of arsenic or selenium and, again, these samples were collected in close proximity to the smelters. Lead, zinc and fluoride concentrations were within normal limits for the respective plant species.

- At Skead and Garson, several soil samples contained excessive amounts of arsenic. Soil samples from Sudbury (1972) and Garson (1970) contained the highest concentrations of selenium but these were not considered to be excessive. However, some values for these elements were elevated in relation to control sample values. Calcium and magnesium values for the soil samples were low and were considered to be related to low soil pH values.

- The soil pH was found to be low at all sampling locations in the study area, including the pH values obtained at control locations (Blind River and Mattawa). Considerable variation in pH values was noted from collection to collection, with the majority of samples having pH values in the range of 4.0 to 5.5.

4.4.1.3 Summary of Impact on the Terrestrial Ecosystem

Over 90 years of smelter emissions, together with natural occurrences (fires, erosion) and inadequate forest management, have severely modified the vegetation and soils of the Sudbury Basin. The following statements summarize the current knowledge:

- In the years prior to 1972, acute and chronic vegetation injury occurred within an elliptical area which had its outermost limit at a distance of 70 km northeast of Sudbury (28). Vegetation injury since 1972 has been reduced to the extent that current injury occurs infrequently, being confined to relatively small isolated areas and affects only those plant species which are most sensitive to SO_2.

- Although there is evidence of contamination of vegetation with Cu and Ni in the immediate Sudbury area due to smelter emissions, more recent studies suggest that the degree of contamination is slowly decreasing as a result of reduced emissions.

- The greatest impact on soils in the immediate Sudbury area was observed to be from Cu and Ni, which were often present in excessive amounts. Their concentrations were found to decrease with increasing distance from the smelters.

- Although the data base is limited (35) with respect to contamination of vegetation and soils by Al in the Sudbury Basin, the level of local emissions (10) from the smelting operations and total deposition (19, 21) of Al in this area could be significant. This concern is based on recent findings (36) in Central Europe regarding the mobilization of Al ions in soils as a result of acid precipitation and its suggested adverse impact on soils and forest ecosystems. Studies to investigate the possible impact of Al on vegetation and soils in the Sudbury area are presently underway as part of Ontario's acid rain program.

- The extensive build-up or accumulation of heavy metals in the soil close to the Sudbury area smelters is aggravated by the increase in soil acidity and could result in:

  a) significant changes in soil composition and its micromorphological (physical) structure and chemistry (34);

b) severely reduced levels of soil microflora and microfauna;

c) the alteration of soil nutrient cycles;

d) severe restriction of the vegetation regenerative potential of these soils.

As is the case for vegetation, some improvement in soil contamination has been noted since 1972, and recent revegetation efforts on barren soil areas are proving successful when soil ameliorative techniques (liming, fertilizing and seeding) are employed. Since 1978, a large scale land reclamation project has been carried out in the Sudbury area and some 1550 ha have been limed, fertilized and seeded to grass. The clean-up of damaged sites and development of grass cover have been judged to be highly effective in improving the appearance and the environment of the Sudbury Area.

Therefore, on the basis of current knowledge with respect to the terrestrial impact in the Sudbury area from smelter emissions, the following statements with respect to local emissions can be made:

SO_2 Emissions

- Ontario currently has a stringent standard and stringent desirable ambient air quality criteria for atmospheric SO_2. The standard (0.30 ppm for a 30 minute average) and the criteria (0.25 ppm for 1 hour; 0.10 ppm for 24 hours and 0.02 ppm for 1 year) have been established to prevent adverse effects with regard to both human health and vegetation. It is not expected that acute or chronic effects would occur on vegetation exposed to atmospheric SO_2 at concentrations below the established standard and criteria.

Metal Emissions

- It is difficult to suggest emission objectives for metals on the basis of terrestrial impact since the problem of vegetation and soil contamination is believed to be largely historical. Revegetation of barren soils will come about most readily through remedial programs similar to those already underway in the Sudbury Area. Since improvements have been noted as a result of reduced emissions during the 1970's, it is appropriate to suggest that the burden on the terrestrial environment from heavy metals will decrease concurrently with decreasing metal emissions and acidic deposition.

4.4.2 Aquatic Effects

Studies (3, 4) in the early 1960's indicated that lakes and ponds had been affected by the mining and smelting activities in and around Sudbury over the past century. Many lakes within 24 km of Sudbury had elevated sulphate levels and reduced pH. It was also found that many lakes in the Sudbury area were contaminated with toxic trace metals, especially copper and nickel (3, 4). Subsequent investigations (6) noted that 70 of 150 lakes in the La Cloche Mountains, 50-100 km southwest of Sudbury, had pH levels less than 5.5, with 33 of these having a pH level less than 4.5. In addition, many lakes equally distant from Sudbury in a northeasterly direction were also acidic (37).

Recognizing the need to better quantify the breadth and scope of the environmental impact on the aquatic ecosystems in the Sudbury area, the Ontario Ministry of the Environment and the Ontario Ministry of Natural Resources began a major investigative study in 1973. The results of these aquatic related investigations are presented in the following sections.

4.4.2.1 Surface Water Quality

4.4.2.1.1 Acidification

Due to their highly resistant geological settings (Precambrian Shield), most of the lakes in the greater Sudbury area are dilute, oligotrophic waters with limited acid buffering or H^+ assimilation capacity. In these dilute lakes, even relatively small additions of acid via the atmosphere are sufficient to cause significant pH reductions. For lakes subjected to acidic loadings, the inherent buffering capacity appears more important in determining the resultant pH than the absolute H^+ input.

Of the 209 lakes investigated during a 1974 to 1976 study (37) covering a radius of 200 km from Sudbury, 20% had calcite saturation indices of greater than 5.0 (CSI - a measure of H^+ assimilation capacity) indicating that they had been critically acidified. An additional 50% had CSI's in the range of 3.0 to 5.0, indicating vulnerability to continuing acidic inputs (37).

The distribution of low pH (pH less than 5.5) lakes was found to exhibit a distinct northeast/southwest pattern with respect to the location of the Sudbury area smelters. This distribution pattern reflects the highly weathering resistant local geology and coincides with observed prevailing surface wind directions. This low pH zone-of-effect includes 30% of the lakes surveyed from 1974 to 1976 and occupies an area of 5300 km^2 amounting to a total lake surface area of about 650 km^2.

From 1973 to 1979, Clearwater Lake near Sudbury was intensively monitored to provide information on long term variability and a reference for manipulation experiments performed on six other Sudbury area lakes (Middle, Hannah, Lohi, Nelson, Mountaintop and Labelle) (22).

All of these lakes were acidic (pH less than 4.6), with the exception of Labelle and Nelson Lakes with pH values of 6.0 and 5.8 respectively (22).

Replacement of HCO_3^- by SO_4^{2-} as the dominant anion in Clearwater Lake, (see Table 4.17), indicated that acidification of the lake was attributable to the deposition of acidic sulphates. Stream chemistry studies conducted on the 11 headwater watersheds of Middle, Clearwater and Nelson Lakes also revealed a dominance of SO_4^{2-} and an absence of HCO_3^- in most streams (22). This result suggested that mineral weathering in the Sudbury area is due to strong acids, rather than by the dissociation of carbonic acid that occurs in watersheds not affected by anthropogenic activities.

On the basis of mass balance models developed to explain the observed chemistry of lakes investigated in this study (22), it was determined that the measured input of mineral acidity to Clearwater Lake in 1977-1978 was sufficient to maintain the lake's alkalinity at about minus 50 ueg L^{-1} (pH of approximately 4.3), which is very near the measured concentration. It can be concluded that the pH of the lake will not increase unless this input of acidity is reduced.

4.4.2.1.2 Metals

The concentrations of nickel and copper in the lakes surveyed from 1974 to 1976 indicated that significant contributions were probably due to the Sudbury area emissions, while the concentrations of cadmium, lead, iron and zinc appeared to be controlled primarily by geological factors (37). From a toxicity viewpoint, copper was the only metal that reached concentrations exceeding Ministry of the Environment objectives for the protection of fish and aquatic life. These levels were recorded in 15% of the lakes. Levels of Al and possibly Cd also reached levels shown to be toxic to fish in laboratory studies.

Bulk deposition measurements performed in the study area from 1976 to 1979 revealed an exceptionally high input of Cu, Ni, Zn, Fe, Mn, and Al to the SES lakes (22). During the period that Inco Ltd. was shut down due to a strike, bulk deposition of Cu and Ni fell to levels as low as those recorded at Muskoka Haliburton, 225 km distant from Sudbury (23). Almost all of the Cu, Ni and Zn, and some of the Fe inputs to the lakes were found to result from direct atmospheric deposition. Further, the atmospheric deposition of strong acid has increased the output of Al, Mn and Fe from the watersheds to the lakes.

Average concentrations of Cu, Ni, Zn, Al and Mn in Clearwater Lake in 1977 were 81, 278, 39, 381 and 290 ug l^{-1} respectively. Trace metal concentrations decreased in the six other lakes (see Table 4.18) with increasing distance from Sudbury, but even in Mountaintop Lake, 50 km from the city, the levels of Zn, Cu and Ni were well above background levels and levels measured in south-central Ontario lakes which are removed from industrial centres but still receive acidic precipitation (23).

On the basis of the best available information on the environmental impact associated with the elevated metal deposition rates observed in the Sudbury area, it is fairly evident that the most sensitive receptors are the aquatic ecosystems. There is ample evidence to indicate severe stress on many Sudbury area lakes due to elevated concentrations of metals.

In order to reduce lake concentrations of metals to those specified as acceptable by the Great Lakes Water Quality Objectives, direct atmospheric inputs of Cu and Ni must be reduced by at least 90%, and inputs of Fe and Zn by 50 to 60% (22). However, some of this Fe and Zn is released from the watersheds to the lakes as a result of the atmospheric deposition of sulphate, such that emission reductions somewhat less than 50 to 60% are required for these elements. A 70% reduction in watershed output of Al is required to decrease lake concentrations of Al to 100 ug l^{-1}. Such a reduction in Al outputs can only be achieved by a large reduction in the deposition of acid sulphate.

4.4.2.1.3 Other Chemical Species

Because of increased weathering rates in the Clearwater Lake watershed, the concentration of major cations (H^+, Ca^{2+}, Mg^{2+}, Na^+, K^+) were much higher in Clearwater Lake (see Table 4.17) than in south-central Ontario lakes and decreased with increasing distance from Sudbury.

It has been shown that bulk deposition of SO_4^{2-} is elevated in the immediate Sudbury area relative to Muskoka-Haliburton due to the influence of local mining/smelting operations (23).

The levels of SO_4^{2-} in Clearwater Lake and in the other SES study lakes decreased with increasing distance from Sudbury (22) (see Table 4.17). The concentration of sulphate was determined to be higher in the Sudbury area study lakes than in south-central Ontario lakes.

A similar trend in the sulphate levels of Sudbury area lakes with increasing distance from Sudbury was observed in a 1974 to 1976 study (37), as shown in Figure 4.2.

4.4.2.1.4 Lake Temperature and Clarity

Clearwater Lake was exceptionally clear. In consequence, the lake had a much thicker epilimnion, a warmer hypolimnion, and fall overturn occurred four to eight weeks earlier than in a non-acidic, oligotrophic lake of similar morphometry and fetch. As the entire lake was included in the trophogenic zone, depression of NO_3^- levels to below detection limits in the hypolimnion was probably attributable to photosynthetic activity in the profundal waters.

4.4.2.2 Lake Sediments

The concentrations of Cu, Ni and Pb in the sediments were observed to have increased by one to two orders of magnitude relative to background levels. Cd, Fe, and Zn concentrations also increased, but by lesser amounts, generally by one order of magnitude. The deposition rates to the sediments of Cu, Ni and Pb were also found to have increased by one to two orders of magnitude relative to background levels. These increases were found to coincide with a decrease in the concentration of Al in lake sediments. Acidification of the interstitial water of the surficial sediments results in the leaching of Al. The major changes in Cu, Ni, Cd, Fe, Zn, Pb, and Al occurred simultaneously, approximately 50 ± 15 years ago. These changes appear to coincide chronologically with the increased level of activity of the smelting industry referred to earlier.

The sedimentation rates in Lohi and Clearwater Lakes (22) increased dramatically (by 200 to 400%) about 40 to 50 years ago. This period roughly coincides with the opening of the Falconbridge smelter and the commissioning of taller stacks at the Copper Cliff smelter. Prior to these changes, the sedimentation rates were typical for oligotrophic Precambrian Lakes (5 to 10 mg cm^{-2} yr^{-1}). The sedimentation rates, as determined by cores that had no mixing zone in the upper layers, declined to the early levels in approximately the last two decades.

The extra sediment responsible for these increased sedimentation rates is believed to consist of material displaced from the lakes' watersheds as a result of increased leaching and erosion of the overburden in the vicinity of these watersheds. In turn, the increased leaching and erosion likely resulted from increased input of strong acid to the watersheds, largely related to the emissions from Sudbury area smelters, and also from the impact of the smelting and lumbering activities on the vegetation at that time.

With respect to the nutrient content of the lake sediments, the concentration of total phosphorus increased greatly at that time mainly because of the increases in sedimentation rates, then decreased to rates that were lower than those indicated as background rates more than 45 years ago. A much smaller decline in total nitrogen content was observed, but generally the concentration pattern was less consistent than the one for phosphorus. The very recent increases in total phosphorus, and particularly in total nitrogen, noted in the uppermost sediment layer in Lohi Lake, reflect the effect of the neutralization experiments performed on this lake by the Ministry. The organic content, as well as the phosphorus and nitrogen concentrations of the sediments of Middle and Hannah Lakes, decreased at about the same time as the metal concentrations increased. The rapid increase in the concentration of these three parameters in the most recent sediments is attributable to the neutralization and fertilization treatments of these lakes, also performed by the Ministry (22).

The lake sediment studies have revealed the adverse impact of the Sudbury area smelter emissions on the sediment chemistry and the sedimentation rates in lakes near Sudbury.

4.4.2.3 Aquatic Biota

4.4.2.3.1 Phytoplankton and Zooplankton

Several investigators have demonstrated that a reduction in lake pH results in a reduction in the richness or diversity of the phytoplankton community especially at pH levels less than 5.5 (38, 39 ,40). In the Sudbury lakes, taxa were identified only to the generic level. However, the same trends were evident (22).

Lohi, Middle, Hannah and Clearwater Lakes (the acidified and copper and nickel contaminated lakes) had a slightly lower average number of genera per collection than Mountaintop Lake (no metal contamination), suggesting that some of the reduction in richness observed in acidic lakes may have been attributable to their contamination with metals.

As lakes acidify, dinoflagellates usually replace the chrysophytes and diatoms that are typically dominant in non acidic lakes (41, 42, 43, 44). In the Sudbury acid lakes, dinoflagellates were the dominant taxa in terms of relative contribution to the total biomass in Clearwater Lake on average. It is not understood why dinoflagellates become dominant in the phytoplankton after acidification.

The biomass of the Sudbury lakes with pH less than 5.5, averaged over the ice free season, did not differ significantly from the biomass measurements taken from Precambrian Shield Lakes with pH greater than 5.5, suggesting that acidification does not result in a reduction in total biomass. The productivity of Clearwater Lake is also similar to that of a non-acid, nutrient poor lake.

Blooms of benthic and attached algae are quite common in acidified waters. The causes for these phenomena are not known, however, the following hypotheses have been forwarded (45, 46):

a) reduced grazing by invertebrates
b) reduced rates of bacterial decomposition
c) succession to more acid tolerant species.

Acidification results in the reduction of the diversity of zooplankton communities as it does in phytoplankton communities (47, 48, 49). Species richness in the acid and metal contaminated SES lakes was reduced. The average number of species of planktonic crustacea observed was three to four times less than in morphometrically similar, oligotrophic, non-acidic lakes in Muskoka-Haliburton. Rotifers were much more important components of the zooplankton than in the non-acidic lakes. The lakes are in the same faunistic region with respect to zooplankton biomass and community assemblages (50).

In contrast with phytoplankton, zooplankton standing stocks were reduced because of low densities and smaller size of the community dominants.

Reductions in fish diversity (see section on fisheries) may have a direct influence on other trophic levels. The number of species of fish strongly correlated with numbers of zooplankton species in lakes in the La Cloche Mountains. Hence the simplification of zooplankton communities in acidic lakes might not simply be the result of sensitivity of zooplankton to depressed pH.

4.4.2.3.2 Macrophytes

Macrophyte standing stock was much higher in Clearwater Lake than in two non-acidic, oligotrophic lakes in south-central Ontario (22).

Generally, the macrophyte vegetation of the SES lakes was similar in structure, but impoverished in species, to the vegetation of 24 clear and coloured, low alkalinity lakes in south-central Ontario. Dense, low-statured mats of isoetid forms predominated.

Contrary to observations made in Swedish acidic lakes (51, 52), extensive beds of Sphagnum were not observed in the study lakes; however, other moss species formed a significant part of the vegetation in Lohi and Clearwater Lakes.

4.4.2.3.3 Microbiology

A preliminary microbiological study was conducted to gain background information on populations of microorganisms important to the aquatic ecosystem, and to determine their roles in the cycling of certain elements in four selected lakes in the Sudbury region (53).

One pair of lakes (Nelson - Fairbanks) was selected for comparison on the basis of geographic location from the smelters (hence, inputs of airborne contaminants); the other pair (Nellie - Bassoon) varied in geological characteristics of their basins. One of the lakes in each pair was acid-stressed (Nelson and Nellie), the other of neutral pH (Fairbanks and Bassoon).

The lakes were compared for the following: number of heterotrophic bacteria, sulphate-reducers, acidophilic autotrophic sulphur oxidizers, yeasts and moulds. The comparatively low populations of chemoautotrophic and heterotrophic micro-organisms found in these ecosystems indicated a low microbial productivity and slow rate of nutrient recycling. However, differences in counts for any parameter could not be explained solely due to acidity or trace metal concentration.

Other researchers (54, 55, 56) have found no apparent reductions in the heterotrophic micro-organism densities in acidified waters.

4.4.2.3.4 Fisheries

The effects of low pH and associated toxicity of increased trace metal concentrations on fish are probably the most dramatic of the impacts of acidification. Based on available literature, the authors of the Extensive Monitoring Survey (37) suggest that, below pH 5.5, reproductive success of fish is impaired and at pH less than 5.0, most fish, particularly salmonids, are eliminated (57). Comparison of the present pH data with these guidelines indicates that 20% of the surveyed study lakes (37) are unsuitable for survival of most fish species and the ability of an additional 10% to maintain viable fisheries is questionable.

The aurora trout (Salvelinus fontinalis timagamiensis (Henn and Richenbach)) had its natural habitat in the large zone with depressed pH (less than 5.5) (58). It is now generally accepted that acidification led to the extinction of this subspecies of the brook trout in these lakes.

There is strong evidence to suggest that even less acidic conditions are capable of causing serious harm to fish populations. It was found that brook trout had an overall reduction in recruitment of 43% at a pH of 6.0 (59). This change in reproductive capacity consisted of decreases in egg production, egg viability, hatching and fry survival.

The effects of low pH on survival and reproduction have also been documented in flagfish, a laboratory test species (60). Overall recruitment was reduced by about 32% at a pH of 6.0 as compared to control (pH = 6.8) conditions.

The consideration of biological effects of acidic precipitation is confounded by the occurrence of high levels of trace metals, due to atmospheric input from smelter emissions, input from watersheds, as well as increased metal dissolution from the sediments at low pH (61, 62). Chronic effects of sublethal metal levels as well as the additive, and possibly synergistic effects of low pH and trace metals, are of major concern and require considerable research for adequate clarification. High Al concentrations, due to dissolution in the watershed, are responsible for fishkills (63) through disruptions in ionic balance and the formation of mucous on gills causing respiratory distress. As seen earlier (Table 4.18), the levels of trace metals, including Al, were found to be elevated in the six SES lakes surveyed in the Sudbury area.

The occurrence of relatively high zinc and copper concentrations (from smelter emissions) in some study lakes is of concern since these metals are highly toxic to aquatic biota (37).

Studies have indicated that the effects of copper on reproduction, growth and survival of fathead minnows are more pronounced in soft water, as less $CaCO_3$ is available for complexation of the metal (64, 65). Additional data indicate that synergistic toxicity of metals would be expected, especially in soft water, and therefore, although the concentrations of other metals present may be low, a metal effect may still exist (66, 67).

Age/class composition of fish typically shifts to older animals in acid stressed waters as a consequence of failed recruitment in the population. Laboratory experiments (60) demonstrated a cessation of flagfish spawning and egg production under conditions of copper (Cu^{2+}) and acid stress. In addition, significant mortalities were observed during the exposure regimes. Although no direct cause could be ascertained, the combined effect of the acid/copper stress on a marginally healthy population could be a possible reason for some of the observed mortality. The significance of such an acid/copper stress to a population of questionable health may well be important as low level disease is endemic in the wild and reproductive functions would then be more seriously affected.

4.4.2.4 Summary of Impact on the Aquatic Ecosystem

Sudbury area lake monitoring data indicate the extensive influence of mining and smelting activities on these waters.

In particular, a large number of the lakes in the greater Sudbury area are dilute, oligotrophic waters with limited acid buffering or H^+ assimilation capacity, due to their highly resistant geological settings (Precambrian Shield). Therefore, even relatively small additions of acid via the atmosphere to these dilute lakes are sufficient to cause significant pH reductions. In lakes subjected to acidic loadings, the inherent buffering capacity appears more important in determining the resultant pH than the absolute H^+ input.

Of the more than 200 lakes investigated, 20% had calcite saturation indices (CSI* - a measure of H^+ assimilative capacity) indicating that they are critically acidified. An additional 50% had CSI's indicating vulnerability to continuing acidic inputs. In addition, a number of lakes had elevated levels of Cu, Ni, Zn, Fe, Mn, Al and SO_4^{2-} which were attributed to the activities of the smelting industries in the Sudbury area.

The distribution of low pH lakes, (pH less than 5.5), exhibits a distinct northeast/southwest trend from the smelting centre. This is a reflection of the local geology which is highly resistant to mechanical and chemical weathering. In addition, this low pH lake distribution may reflect the influence of prevailing ground level wind direction. This low pH zone-of-effect occupies an area of 5,300 km^2 which contains a lake surface area of 650 km^2. Within the zone, which includes 30% of the study lakes, significant loss and depression of fish populations and associated biota have occurred.

The distribution of metals in the study lakes provides a further concern relative to impacts on the aquatic biota. Sediments and water column concentrations of nickel and copper showed significant elevations associated with smelting activity. From a toxicity viewpoint, copper levels exceeding M.O.E. objectives for protection of fish and aquatic life were recorded in 15% of the lakes.

Significant reductions in metal emissions from Sudbury sources are required, especially for Cu and Ni, in order to reduce Sudbury area lake concentrations of metals to those specified as acceptable by the Great Lakes Water Quality Objectives.

Sediment studies conducted on Lohi and Clearwater lakes revealed that drastic increases in sedimentation rates and concentrations of Cu, Ni and Pb (and, to a lesser degree, Cd, Fe and Zn) occurred approximately 40 to 50 years ago, roughly coincident with the opening of the Falconbridge smelter and the commissioning of taller stacks at the Inco Copper Cliff smelter.

The depressed pH and elevated metal conditions revealed an adverse impact on phytoplankton and zooplankton communities. A significant number of Sudbury area lakes were found to be unsuitable for the survival and reproduction of most fish species.

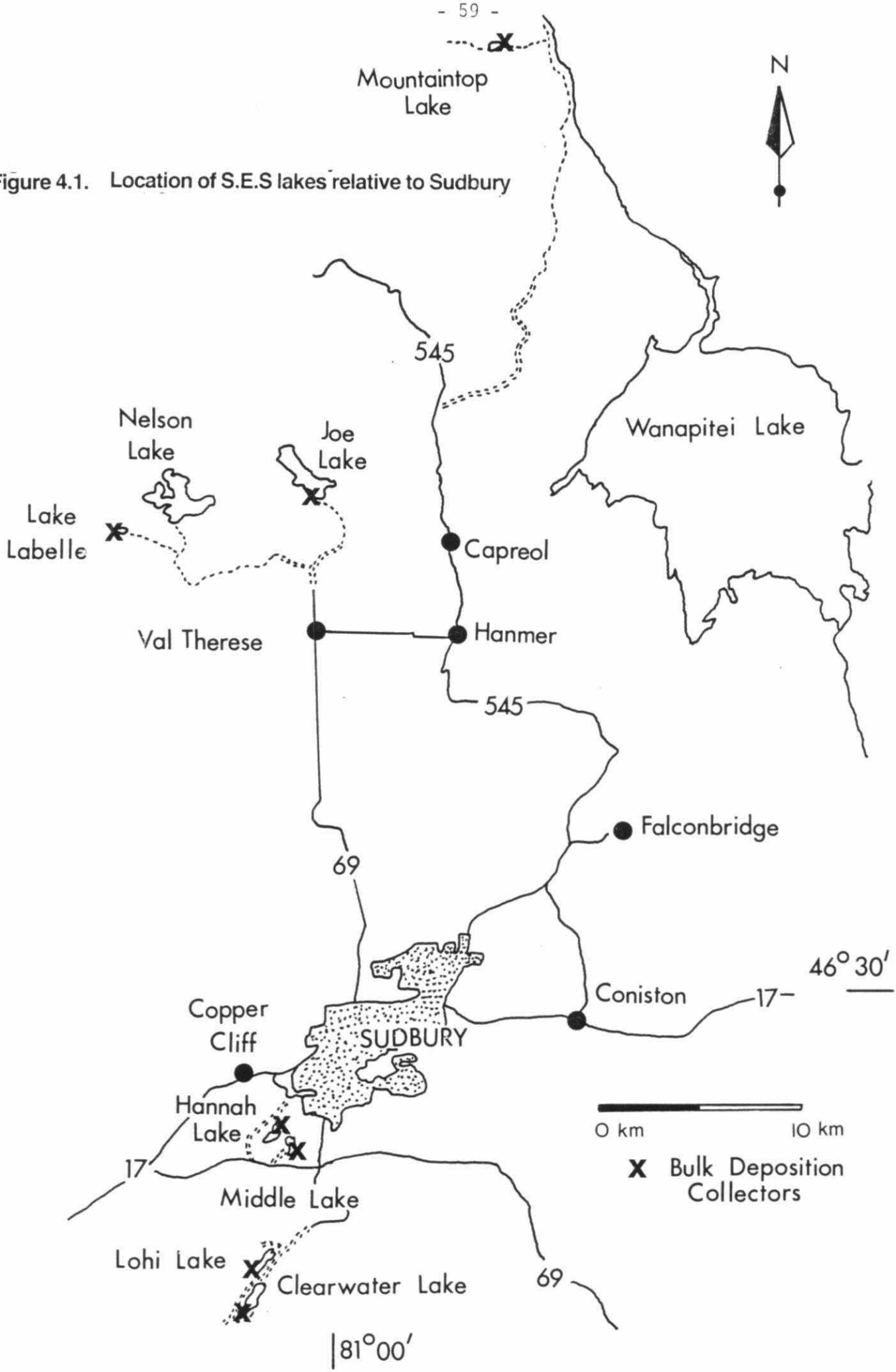

Figure 4.1. Location of S.E.S lakes relative to Sudbury

Figure 4.2. Plot of surface water sulphate concentrations as a function of distance from Sudbury

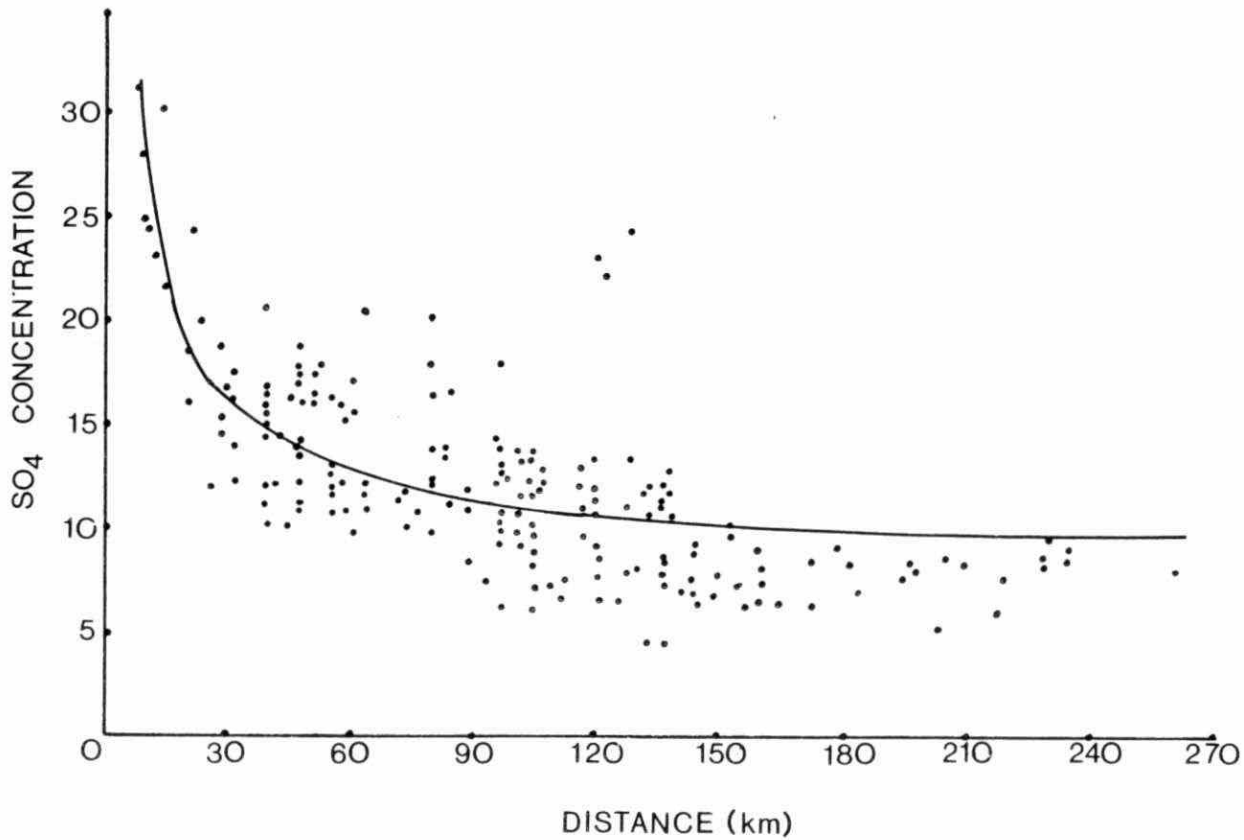

Table 4.1. Yearly emissions of major pollutants in the Sudbury Basin in tonnes for the period 1973 to 1981

Source	Variation	Sulphur dioxide [o]	Sulphuric acid	Total Particulate	Iron	Copper	Nickel	Lead	Arsenic
Inco 381 m	Maximum	1,185,449	14,541	14,494	1,454	350	342	298	201
	Average	885,667	7,270	11,417	990	245	228	184	114
Stack*	Minimum	383,000	3,241	6,491	201	70	53	88	70
Inco 194 m	Maximum	104,390							
	Average	54,568	1,664	2,380	643	171	226	6	4
Stack	Minimum	18,980							
Inco Smelter	Maximum	16,000		755	90	312	40	0.8	0.1
	Average	12,000	88	586	70	242	31	0.6	0.1
(Low Level)	Minimum	6,000		283	34	117	15	0.3	0.1
Falconbridge	Maximum	274,000							
93 m	Average	173,000	438	865	98	11	9.6	13.4	6.4
Stack	Minimum	88,000							
Inco Two 45 m Stack**	Average	-	-	(4,073)	(2,354)	-	-	-	-
TOTAL	Average	1,125,235	9,460	15,248	1,801	669	500	204	125

Basis: 365 days x 24 hours/day production.

* Oxides of nitrogen emissions expressed as NO_2 = 3,281 tonnes.

* Hydrogen chloride emissions = 530 tonnes.

* Emissions of particulates, iron, copper and nickel from the 381 m stack are yearly values calculated from correlations with sulphur dioxide emissions. Emissions of sulphuric acid, lead and arsenic are average measured values.

** Emissions ceased in April 1980, not included in average.

o Except for Inco Smelter (low level), all sulphur dioxide emissions were obtained by mass balance calculations. Annual low level ammonia emissions from Inco's iron ore recovery plant in 1977 was 4,219 tonnes.

Table 4.2. Yearly emissions of sulphur dioxide from major industrial sources in the Sudbury Basin in thousands of tonnes

Year	Inco 381 m Stack*	Inco Low Level Smelter**	Inco 194 m Stack*	Falconbridge 93 m Stack*+
1973	1,171	14	104	274
1974	1,126	16	74	258
1975	1,141	16	40	195
1976	1,163	15	41	191
1977	1,069	15	52 (55***)	200
1978	535	8	24	117
1979	383	6	19	88
1980	733	11	66	123
1981	650	9	64	114
Average	885	12	54	173
% of total	78	1	5	16

* Determined by mass balance calculations.
** Determined from measurements in 1978 and 1979 and prorated to other years on the basis of production.
*** Determined from stack measurements.
\+ Falconbridge low level emissions assumed to be about 2% of smelter emissions.

Table 4.3. Yearly emissions of total particulates in tonnes from major sources in the Sudbury Basin from 1973 to 1981

Year	Inco 381 m Stack	Inco Smelter Low Level Emissions	Inco 194 m and two 45 m Stacks	Falconbridge 93 m Stack
1973	12,166	650		
1974	14,144	730		
1975	14,299	755		
1976	14,494	721		
1977	13,763	703	2,380**	
1978	8,057	387		
1979	6,491	283	4,064*	865
1980	10,096	548		
1981	9,241	497		
Average	11,417	586		
Standard Error of Estimate	Sxy = 4,588			

* Emissions from two 45 m stacks, not applicable after April 1980 due to plant shutdown.
** These emissions were decreased in 1980 as a result of additional precipitator capacity at the nickel refinery.

Table 4.4. Average emissions of metals from major Sudbury sources in kilograms/hour

Source	Iron	Copper	Nickel	Lead	Arsenic	Total	Percent of Contribution
Inco 381 m Stack	113 Sx,y = 109.5*	28 Sx,y = 19.8*	26 Sx,y = 16.4*	21 σ = 8.6**	13 σ = 5.5**	201	53.5
Inco 194 m Stack[o]	73	19.5	26.2	0.7	0.4	119.8	31.9
Inco Smelter Building (Low Level)	8	28	3.5	0.1	0.01	39.6	10.5
Falconbridge 93 m Stack	11	1	1	1.5	0.8	15.3	4.1
Inco Two 45 m Stack	(268.8)[+]						
TOTAL	205	76.5	56.7	23.3	14.2	375.7	

* Sx,y = standard error of estimate.

** σ = Standard deviation.

[o] Emissions measured in 1977, inapplicable after the installation of new electrostatic precipitators at the nickel refinery in 1980.

[+] Emissions inapplicable after the pellet plant shutdown in 1980. Excluded from total.

Table 4.5. Average emissions of five major metals from the Inco 381 m stack in kilograms/hour

Year	Iron*	Copper*	Nickel*	Lead	Arsenic
1973	127	31	29	21	11
1974	163	39	37	29	10
1975	166	39	38	23	23
1976	169	39	39	12	15
1977	156	37	35	18	8
1978	52	14	12	10	-
1979	23	8	6	-	-
1980	89	22	21	34	10
1981	73	19	17		
Average	113	28	26	21	13

* Emissions calculated from regression lines.

Table 4.6. Sulphur dioxide levels measured at the Ash Street and Skead Monitoring Stations during the period 1971 to 1981

	ASH STREET		SKEAD	
Year	SO_2 Avg (ppm)*	No. of Hours Above Criterion**	SO_2 Avg (ppm)*	No. of Hours Above Criterion**
1971	0.053	377	0.045	242
1972	0.028	164	0.025	97
1973	0.017	42	0.013	40
1974	0.033	81	0.018	163
1975	0.028	53	0.016	86
1976	0.019	47	0.021	154
1977	0.015	25	0.017	161
1978	0.012	24	0.011	86
1979	0.012	8	0.012	65
1980	0.016	19	0.011	54
1981	0.010	18	0.011	81

* Annual criterion = 0.02 ppm
** 1 Hour criterion = 0.25 ppm

Table 4.7. Ambient concentrations of Cu, Ni, and Fe from high-volume air filters exposed in the Sudbury area from 1976 to 1981

Element	Station	Geometric Mean (ug m^3) 1976	1977	1978	1979	1980	1981
Cu	Ash St. (Sudbury)	0.5	0.5	0.2	0.3	0.5	0.2
	Lisgar St. (Sudbury)	0.4	0.5	0.3	0.2	0.2	0.3
	Copper Cliff	1.4	0.8	0.6	0.3	0.7	0.5
	Falconbridge	1.0	0.6	0.2	0.2	0.4	0.3
Ni	Ash St. (Sudbury)	0.14	0.15	0.02	0.03	0.03	0.05
	Lisgar St. (Sudbury)	0.13	0.08	0.03	0.02	0.07	0.05
	Copper Cliff	0.23	0.17	0.10	0.07	0.33	0.17
	Falconbridge	0.18	0.18	0.05	0.04	0.07	0.03
Fe	Ash St. (Sudbury)	1.3	1.0	1.2	0.6	0.9	1.0
	Lisgar St. (Sudbury)	1.9	1.2	1.0	0.9	1.3	1.0
	Copper Cliff	2.8	2.3	1.1	1.0	1.5	1.2
	Falconbridge	3.1	2.8	1.2	0.8	1.0	0.6

Table 4.8. Results of the cumulative wet precipitation sampling program

Substance	Range (mg l^{-1})	Geometric Mean (mg l^{-1})
Sulphate	0.3 - 18.0	3.49
Nitrate (as N)	0.3 - 3.0	0.60
Ammonium (as N)	0.01 - 3.1	0.34
Iron	0.006 - 1.4	0.068
Copper	0.001 - 1.1	0.003
Nickel	0.001 - 0.079	0.002
Lead	0.001 - 0.067	0.011
Zinc	0.001 - 0.31	0.010

Table 4.9. A comparison of the cumulative wet precipitation sampling results for the periods June 1978 to May 1979 and June 1979 to May 1980

Parameter	Geometric Mean (mg l^{-1})*	
	June 1978 to May 1979	June 1979 to May 1980
pH	4.1	4.2
Sulphate	3.4	3.4
Nitrate (as N)	0.6	0.6
Ammonium (as N)	0.3	0.4
Iron	0.06	0.07
Copper	0.003	0.004
Nickel	0.001	0.002
Lead	0.013	0.009
Zinc	0.011	0.009

* units are mg l^{-1} except for pH.

Table 4.10. Average wet deposition of Inco emissions within a 40 km radius of the smelter per precipitation event.

Substances	Emitted (kg)	Deposited (kg)	% Emissions Removed	% Inco Contribution to Total Wet Deposition
H_f*	4.5×10^2	1.4×10^2	32	6
S	5.2×10^5	3.4×10^3	0.7	8
Fe	7.1×10^2	4.8×10^2	68	20
Cu	2.6×10^2	2.7×10^2	100	69
Ni	3.5×10^2	1.3×10^2	36	67
Pb	2.1×10^2	0.7×10^2	33	14
Zn	0.55×10^2	0.5×10^2	93	12
Al	3.9×10^2	1.8×10^2	80	8
Cd	0.16×10^2	0.04×10^2	23	28
Cr	0.52×10^2	0.01×10^2	2.3	8

* Free hydrogen, calculated from pH measurements.

Table 4.11. Dry deposition of Inco and Falconbridge emissions within 40 km of the sources

	Parameter	Average Daily Emissions (kg)	Estimated Dry Deposition (kg)		% Emission Deposited	Smelter Deposition as % of Total*
			Average Downwind of Smelter	Average Upwind of Smelter		
Inco	SO_2	2.3×10^6	4.0×10^3	10.4×10^3	0.17	28
	SO_4	4.9×10^4	37	400	0.08	8.5
	total S	1.2×10^6	2.0×10^3	5.3×10^3	0.17	27
	Fe	1.6×10^3	280	1.3×10^3	17	18
	Ni	800	38	11	4.8	78
	Pb	480	0.75	4.1	0.16	15
	Zn	120	0.23	2.5	0.18	8.4
	Al	410	30	520	7.4	5.4
	Cd	37	0.007	0.15	0.02	4.5
Falconbridge	SO_2	2.9×10^5	3.2×10^3	10.4×10^3	1.1	23
	SO_4	4.7×10^3	19	240	0.40	7.4
	total S	1.5×10^5	1.6×10^3	5.3×10^3	1.1	23
	Fe	100	140	1.1×10^3	140	11
	Ni	14	7.5	11	54	40
	Pb	37	1.4	5.0	3.8	22
	Zn	5.7	0.13	3.2	0.23	3.9
	Al	32	15	420	47	3.5
	Cd	12	0.006	0.15	0.05	3.9

* (Inco Deposition)/(Inco Deposition + Upwind Deposition) x 100%
or
(Falconbridge Deposition)/(Falconbridge Deposition + Upwind Deposition) x 100%

Table 4.12. Range, number of samples (N), and mean concentration of ions, nutrients and heavy metals in bulk deposition and wet-only precipitation samples collected at Sudbury North, Center, and South for 1976-1979.

[Ion concentrations are in meq l^{-1} and nutrient and heavy metal concentrations are in mg l^{-1} (22).]

Parameter	Sudbury North Range	n	Mean	Sudbury Center Range	n	Mean	Sudbury South Range	n	Mean
bulk H^+	0.001-0.251	105	0.051	0.002-0.316	167	0.058	0.002-0.316	146	0.062
wet H^+	0.002-0.200	43	0.055	0.025-0.251	34	0.071			
bulk Ca^{++}	0.002-0.099	87	0.026	0.002-0.250	150	0.038	0.002-0.078	133	0.029
wet Ca^{++}	0.001-0.050	43	0.022	0.004-0.067	32	0.028			
bulk Mg^{++}	0.001-0.041	87	0.007	0.001-0.045	146	0.009	0.001-0.082	131	0.007
wet Mg^{++}	0.008-0.0164	43	0.005	0.008-0.016	33	0.007			
bulk Na^+	0.006-0.083	84	0.023	0.001-0.174	142	0.040	0.005-0.252	121	0.012
wet Na^+	0.004-0.039	43	0.012	0.000-0.047	33	0.014			
bulk K^+	0.000-0.034	85	0.003	0.000-0.020	146	0.003	0.000-0.037	125	0.004
wet K^+	0.003-0.004	41	0.002	0.001-0.008	35	0.002			
bulk SO_4^{2-}	0.002-0.250	103	0.080	0.016-0.354	166	0.076	0.015-0.210	139	0.091
wet SO_4^{2-}	0.010-0.177	42	0.005	0.019-0.207	33	0.083			
bulk Cl^-	0.001-0.045	88	0.008	0.001-0.068	147	0.026	0.001-0.087	126	0.011
wet Cl^-	0.001-0.020	42	0.005	0.002-0.019	34	0.008			
bulk total P	0.001-0.445	100	0.0397	0.001-0.414	165	0.014	0.001-0.650	137	0.476
wet total P	0.001-0.050	42	0.0127	0.003-0.052	32	0.018			
bulk NO_3^--N	0.042-3.150	84	0.552	0.065-1.70	129	0.594	0.065-2.52	102	0.615
wet NO_3^--N	0.077-2.475	30	0.440	0.11 -1.20	26	0.507			
bulk NH_4^--N	0.010-1.20	100	0.375	0.072-1.71	158	0.490	0.035-2.42	132	0.473
wet NH_4^--N	0.024-0.90	41	0.330	0.132-1.38	33	0.467			
bulk TKN	0.021-4.50	100	0.656	0.125-2.65	145	0.748	0.132-4.40	129	0.778
wet TKN	0.080-1.64	39	0.525	0.26 -1.35	30	0.596			
bulk Fe	0.010-0.480	95	0.068	0.01 -2.60	157	0.267	0.010-1.90	138	0.173
wet Fe	0.010-0.190	41	0.040	0.01 -0.31	34	0.061			
bulk Mn	0.001-0.110	46	0.010	0.001-0.060	95	0.010	0.002-0.034	95	0.008
wet Mn	0.001-0.028	29	0.005	0.002-0.015	29	0.006			
bulk Al	0.004-0.680	97	0.044	0.008-2.20	158	0.107	0.002-0.440	142	0.059
wet Al	0.004-0.180	43	0.024	0.004-0.18	36	0.038			
bulk Cu	0.001-0.240	102	0.030	0.001-1.600	176	0.182	0.001-0.830	149	0.089
wet Cu	0.001-0.054	42	0.013	0.001-0.170	36	0.050			
bulk Ni	0.001-0.093	98	0.007	0.002-0.780	175	0.073	0.001-0.720	147	0.045
wet Ni	0.001-0.023	42	0.005	0.002-0.091	36	0.023			
bulk Zn	0.001-0.530	102	0.059	0.001-0.410	174	0.056	0.001-0.370	144	0.051
wet Zn	0.002-0.064	43	0.008	0.002-0.160	36	0.017			
bulk Pb	0.003-0.120	45	0.021	0.004-0.190	86	0.031	0.004-0.150	80	0.029
wet Pb	0.004-0.056	30	0.017	0.009-0.074	27	0.024			

wet-only precipitation samples collected between May and November of 1977, 78 and 79.

Table 4.13. List of SO_2 concentrations and averaging periods equivalent to a fumigation intensity of 100

Average SO_2 Concentrations (ppm)	Averaging Period (hours)
0.95	1
0.55	2
0.35	4
0.25	8

Table 4.14. A summary of potentially injurious fumigations recorded in the Sudbury area from 1965 to 1981

YEAR	NUMBER OF POTENTIALLY INJURIOUS FUMIGATIONS	NUMBER OF SO_2 MONITORS
1965	42	10
1966 (strike year-Inco)	35	10
1967	73	10
1968	50	10
1969 (strike year-Inco and Falconbridge)	34	10
1970	64	10
1971	88	11
1972*	36	12
1973**	8	13
1974	17	14
1975 (strike year-Inco and Falconbridge)	9	16
1976+	19	17
1977+	19	17
1978+ (strike year-Inco)	7	17
1979+ (strike year-Inco)	3	17
1980+	5	15
1981*	1	15

*Summer vacation shutdowns (Inco and Falconbridge)
** Summer vacation shutdown (Inco)
+Production shutdown (Falconbridge)

Table 4.15. Complaints diagnosed as SO_2 injury during the period 1970-1981

YEAR	COMPLAINTS DIAGNOSED AS SO_2 INJURY
1970	9
1971	10
1972	15
1973	15
1974	20
1975	6
1976	6
1977	2
1978	2
1979	1
1980	0
1981	1

Table 4.16. List of elements and recommended concentration guidelines in vegetation and soil

Contaminant	CONCENTRATIONS CONSIDERED EXCESSIVE (ppm, dry weight)	
	Vegetation (not washed foliage)	Surface Soil (0-5 cm)
Aluminum	400	-
Arsenic	5	20
Cadmium	5 (3 rural)	8 (5 rural)
Cobalt	10	25
Copper	30	100
Iron	800	-
Lead	100 (50 rural)	600 (150 rural)
Nickel	25 (15 rural)	100 (70 rural)
Selenium	2	3
Zinc	200	600 (300 rural)

Table 4.17. Conductivity and major ion content of S.E.S.

Conductivity and major ion content (ueq l^{-1}) of SES lakes (mean with standard error in parentheses). Distances from Sudbury are indicated.

	Hannah[1] 1974	Middle[2] 1973	Lohi[2] 1973	Clearwater[1] 1977	Labelle[3] 1977	Nelson-1[1] 1975	Mountaintop[3] 1976	Experimental Lakes Area	Muskoka-Haliburton
Distance from Sudbury (km)	4.3	5.0	11	13	27	28	52		
Conductivity (umhos cm^{-1} 25°C)	166	131	88	89	51	46	45	19	33
Ca^{2+}	570 (5.0)	490 (7.5)	310 (5.0)	285 (4.5)	255 (6.5)	205 (3.0)	150 (16)	80	150
Mg^{2+}	295 (3.3)	410 (24)	205 (22)	115 (8.2)	91 (1.6)	82 (0)	82 (0)	74	72
Na^{+}	152 (7.8)	104 (7.8)	83 (6.5)	70 (1.3)	48 (1.3)	42 (1.7)	43 (0)	39	36
K^{+}	54 (2.0)	49 (4.3)	33 (2.3)	18 (0.3)	16 (0.5)	12 (0.3)	11 (0)	10	13
H^{+}	51 (3.0)	40 (2.9)	41 (1.9)	79 (5.2)	1 (0.2)	2 (0.2)	24 (2.7)	1	1
Sum of cations	1120	1090	672	567	411	343	310	203	271
SO_4^{2-}	1200 (42)	927 (14)	556 (7.1)	550 (6.5)	325 (5.4)	329 (5.8)	292 (7.1)	63	170
Cl^{-}	76 (3.4)	-	-	62 (1.4)	14 (0.6)	12 (0.6)	11 (0)	39	18
NO_3^{-}-N	41 (1.0)	32 (1.8)	6 (0.6)	4 (0.3)	2 (0.7)	2 (0.4)	3 (0.3)	-	-
HCO_3^{-}	0.2 (0.2)	0	0	0	76 (2.2)	40 (3.0)	11 (5.0)	62	110
Sum of anions	1320	-	-	616	417	383	317	164	298

[1] In this and subsequent Tables, data from 1974, not 1973 in Hannah Lake, are employed as this was the last year before manipulations. Data from 1977 in Clearwater Lake are used since after this year, the chemistry may have changed in response to a shutdown of operations of smelters in the Sudbury area.

[2] Pre-addition of base.

[3] Pre-addition of N and P.

Table 4.18. Metal concentrations in S.E.S. lakes

	Hannah	Middle[1]	Lohi[1]	Clearwater	Labelle[2]	Nelson[1]	Mountaintop	Muskoka-Haliburton[3]
	1974[4]	1973[5]	1973	1977[6]	1977	1975	1976	1976-1978
Distance from Sudbury (km)	4.3	5.0	11	13	27	28	52	214
Cu[7]	1108 (17.8)	496 (6.9)	83.6 (5.6)	81.3 (4.4)	4.8 (1.7)	22.0 (3.0)	24.0 (2.0)	2
Ni	1865 (76.1)	1068 (17.6)	254 (10.3)	278 (7.0)	12.7 (1.6)	17.1 (0.9)	12.2 (1.6)	2
Zn	120 (4.3)	91.3 (10.3)	41.6 (5.7)	39.2 (2.5)	10.6 (1.3)	18.3 (1.2)	28.0 (3.1)	5 (3-8)
Fe	47.0 (7.6)	143 (14.9)	320(90[8]) (85.6)	88.2 (7.5)	73.0 (8.5)	60.8 (12.9)	215 (33.8)	98 (20-230)
Al	1097 (61.4)	-	-	381 (9.5)	73.3 (13.2)	86.6 (5.7)	440 -	42 (8-91)
Mn	340 (12.3)	354 (10.3)	284 (10.4)	290 (6.0)	74.8 (10.3)	63.1 (1.8)	120 -	33 (15-71)

[1]Prior to additions of base.
[2]Prior to additions of N and P.
[3]1976-1978 averages (range in brackets) from 15 lakes in Muskoka-Haliburton from Dillon (unpublished data) are presented for comparison.
[4]Data for 1974 are 1 m below surface.
[5]Data for 1973 are 1 m above bottom.
[6]Data for other years are whole lake esimates.
[7]mg m^{-3} mean with standard error in parentheses.
[8]1 m above bottom levels of Fe were possibly affected by anoxic sediment surface. This value is the single whole lake composite value before additions of base.

5. CONSOLIDATION OF STUDY RESULTS FOR SULPHUR DEPOSITION

A clear and concise evaluation of the impact of local smelter emissions on the environment of the immediate and greater Sudbury areas requires consolidating the best available scientific evidence obtained from the results of the studies described in Chapter 4 of this report. To this end, the best estimates of total sulphur deposition at a number of receptor areas in the Sudbury region will be provided, together with the best estimates of the local contribution to total sulphur deposition.

Thereafter, various deposition rate scenarios and the projected impact of each one on lake acidification will be used to arrive at estimates of overall SO_2 emission reductions from Sudbury area smelters required to achieve a number of selected deposition rate levels. This exercise will be carried out using Clearwater Lake since it was the most intensively studied of all the SES lakes; also a calibrated lake model has been successfully developed for this lake by the Ministry. Lastly, the Clearwater Lake case and data derived from extensive surveys (37) will be employed to arrive at an estimate of the total number of similar lakes within the immediate Sudbury area.

5.1 Total Sulphur Deposition

The sulphur present in the substances that eventually reach the earth's surface undergoes chemical transformation processes (oxidation), the result of which is the formation of sulphate (SO_4^{2-}) compounds. Hence, a commonly used approach is to express sulphur deposition as an equivalent SO_4^{2-} deposition. This approach will be used in this Chapter.

The emphasis on SO_4^{2-} deposition is easily justifiable as studies of lakes in eastern North America have provided ample evidence that atmospheric deposition accounts for sulphate levels in excess of those expected from natural processes. Work summarized in the U.S./Canada Memorandum of Intent has identified sulphuric acid as the dominant compound contributing to the long term surface water acidification process. Nitric acid contributes to the acidity of precipitation, but is much less important than sulphuric acid in long term acidification of surface waters. Nitric acid contributes to surface water acidification particularly during periods of snow melt in some areas (68). The atmospheric deposition data and lake monitoring data collected in the Sudbury area, support this conclusion (19, 20, 22, 37).

A summary of the estimates of SO_4^{2-} deposition rates at a few locations in the Sudbury area, and also in the Muskoka-Haliburton area, is presented in Table 5.1 for comparative purposes.

Three locations within a 40 km radius from the Inco smelter were selected as receptor areas on the basis of available deposition data and also, since these locations encompass, in part, what is recognized as the most severely impacted area. Clearwater Lake is located about 12 km southwest of Sudbury (See Figure 4.1.) The Sudbury northeast location is about 10 km northeast of the Inco smelter; the Muskoka-Haliburton area is about 225 km southeast of Sudbury. (See Figure 2.1.)

In order to identify the local (i.e. Sudbury area smelters) contributions to total wet and dry deposition in Table 5.1, the term 'all' was used to represent all sources contributing to deposition including the Sudbury sources, whereas the term 'Sudbury' was used to represent the contributions from Sudbury sources alone.

5.1.1 Wet Deposition

At the Clearwater Lake, Nelson Lake and Sudbury northeast locations, the total wet sulphate deposition was determined to be 30 kg SO_4^{2-}/ha·yr, of which 10% (or 3 kg SO_4^{2-}/ha·yr) is attributed to Sudbury sources. These results were obtained from the event wet deposition studies conducted by the Air Resources Branch and represent an average for wet deposition within a 40 km radius from the Inco smelter in Copper Cliff for the study period, i.e. from June 1978 to May 1980. On average, within about 40 km from the Inco smelter, the long range contributions to wet SO_4^{2-} deposition appear to mask the local contributions. In the Muskoka-Haliburton area, the total wet SO_4^{2-} deposition was determined to be about 20 kg SO_4^{2-}/ha·yr of which 3 kg SO_4^{2-}/ha·yr result from Sudbury SO_2 emissions. These values were obtained from modelling estimates using the long range - long term statistical model developed by the Ministry for 1977 SO_2 emission levels (24).

5.1.2 Dry Deposition

The dry deposition rate values were determined from model estimates. For the locations in the Sudbury area, a 'background' contribution of 19 kg SO_4^{2-}/ha·yr was estimated using a measured ground level background SO_2 concentration of 3 ppb (8 ug m^{-3}). The estimates were derived for the period June 1977 to May 1978 coinciding with other related programs of the Sudbury Environmental Study prior to the extensive labour strike at Inco.

At Clearwater Lake, the total dry deposition of 66 kg SO_4^{2-}/ha·yr was determined from an average of model estimates using the short range - long term dispersion model for the period June 1977 to May 1978 and of the total SO_4^{2-} deposition rates derived from two independent mass balance calculations for the calibrated Clearwater Lake - watershed system over the same time period. For example, the short range - long term model dry deposition rate was estimated as

68 kg SO_4^{2-}/ha.yr, resulting in a total SO_4^{2-} deposition at Clearwater Lake of 98 kg SO_4^{2-}/ha·yr (68 dry and 30 wet). The two most accurate total deposition rate estimates from mass balance calculations for the calibrated Clearwater Lake watershed system (on the assumption that all the missing SO_4^{2-} input into that system comes from dry SO_2 deposition) give deposition rate values of 86 and 105 kg SO_4^{2-}/ha·yr. The average of these two figures and that from the model (total deposition of 98 kg SO_4^{2-}/ha·yr) gives a total deposition rate value of 96 kg SO_4^{2-}/ha·yr. Hence, in view of the degree of accuracy of the model estimates, a figure of 66 kg SO_4^{2-}/ha·yr, instead of the original 68 kg SO_4^{2}/ha·yr derived from the model, was adopted for the dry deposition estimate from all sources to Clearwater Lake. The Sudbury contribution to total dry deposition was estimated to be 47 kg SO_4^{2-}/ha·yr at Clearwater Lake for the period June 1977 to May 1978.

At Nelson Lake, a total dry deposition rate of 33 kg SO_4^{2-}/ha·yr was obtained again using the short range - long term model for the period June 1977 to May 1978. In this case, Sudbury contributions were estimated to be 14 kg SO_4^{2-}/ha·yr. Emissions from the smelters impact less frequently on Nelson Lake than on locations northeast and east of Sudbury.

For the Sudbury northeast location (10 km from the Copper Cliff smelter), the dry deposition model estimates were the highest in the Sudbury area. A local contribution of 105 kg SO_4^{2-}/ha·yr was estimated, again using the short range - long term model for the period June 1977 to May 1978. The addition of the background contribution to this value gave a total dry deposition rate of 124 kg SO_4^{2-}/ha·yr at that location.

At the Sudbury west location (10 km from the Copper Cliff smelter), the dry deposition model estimated for the local contribution was 23 kg SO_4^{2-}/ha·yr again using the short range-long term model for the period June 1977 to May 1978. With the addition of background contributions this gives a total of 42 kg SO_4^{2-}/ha·yr.

For the Muskoka-Haliburton receptor area, a total dry deposition estimate of 19 kg SO_4^{2-}/ha·yr was obtained using the long range - long term statistical model developed by the Ministry for 1977 SO_2 emissions levels. Sudbury contributions were estimated to be about 6 kg SO_4^{2-}/ha·yr and reflect sulphate deposition resulting from the oxidation of SO_2 from the Sudbury 'plume'.

On the basis of estimates using the short range-long term model, the Sudbury contributions to dry deposition decrease to about the same level as the 'background' values (i.e. to 19 kg SO_4^{2-}/ha·yr from Sudbury and 19 kg SO_4^{2-}/ha·yr from other sources) at the following distances and directions from the Inco Copper Cliff smelter:

Quadrant	Distance (km)
N	20
NE	100
E	80
SE	50
S	40
SW	30
W	20
NW	10

The distances at which the dry contribution to the total deposition rate of 38 kg SO_4^{2-}/ha·yr range from 10 km to 100 km and reflect the dominance of west and southwest winds in the Sudbury area. These figures reflect contributions from Sudbury emissions during the period June 1977 to May 1978 and define the geographic region to which Sudbury emissions contribute 50% or more of the total dry deposition.

The dry deposition figures within parentheses for the four Sudbury area locations (Table 5.1) were estimated using the model for the period June 1978 to May 1979. As mentioned previously in this report, Inco was shut down from July 17 to August 27, 1978 and was on strike from September 16, 1978 to June 7, 1979. The data in Table 5.1 show that the Sudbury contribution to dry deposition decreased significantly at these four locations, to the extent that this local contribution was appreciably lower than the 'background' contribution.

The contribution from 'primary sulphates' emitted by Sudbury area smelters (e.g. sulphuric acid, metal sulphate compounds, etc.) using the sulphuric acid emission figures presented in a Ministry report (10) and in Table 4.1, were estimated from the short range-long term model to be less than 1% of the Sudbury contribution to dry deposition. Therefore, contributions to total sulphur deposition from primary sulphates are considered to be insignificant compared to contributions from dry SO_2 deposition.

The most important observations to be drawn from the sulphate deposition data presented in Table 5.1 are the following:

- The dry component of total SO_4^{2-} deposition in the Sudbury area is highly variable. At some locations in the immediate (about 10 km) Sudbury area (e.g. Sudbury NE), the dry component of total SO_4^{2-} deposition can be as much as four times higher than the wet component as a result of the dry deposition of SO_2 emitted from the local smelter sources. At other locations (e.g. Sudbury W) the dry

contribution to total SO_4^{2-} deposition is much lower (dry component is about 1.4 times the wet component). The results reflect the dominance of westerly and southwesterly winds in the Sudbury area.

- The Sudbury contributions to total SO_4^{2-} deposition in the immediate (10 km) Sudbury area, when Inco and Falconbridge are operating, are significant, ranging from 36% to about 70%; the major contribution from Sudbury sources is the dry component which ranges from 32% to about 68% of the total sulphate deposition, within about 10 km from the Copper Cliff smelter.

- The Sudbury contributions to dry deposition are estimated to decrease rapidly with increasing distance from the smelters, approaching background levels (19 kg SO_4^{2-}/ha·yr) at distances of less than 50 km from the Copper Cliff smelter for all directions except for the northeast and east quadrants, where local contributions do not reach 'background' levels for at least 100 km.

- Sudbury sources contribute, on average, about 10% of the total wet sulphate deposition within a 40 km radius.

- On the assumption that Sudbury contributions to both wet and dry deposition are completely eliminated, the Sudbury area within a 40 km radius would be exposed to total sulphate deposition rates of about 46 kg SO_4^{2-}/ha·yr (wet = 27; dry = 19 kg SO_4^{2-}/ha·yr) based on 1977 SO_2 emission levels for 'outside' sources.

- Sudbury SO_2 emissions contributed 9 kg SO_4^{2-}/ha·yr or 23% of the total sulphate deposition in the Muskoka-Haliburton area, based on 1977 emission levels. Other continental SO_2 sources are estimated to result in a total deposition rate of about 30 kg SO_4^{2-}/ha·yr in that area.

5.2 Lake Acidity and Emissions Reduction Scenarios

It is useful to consider various emission reduction scenarios and other deposition rate targets and to apply this exercise to a well studied watershed system in the Sudbury area (Clearwater Lake). This exercise allows an assessment to be made of the impact of reductions of Sudbury emissions on similar aquatic ecosystems.

5.2.1 Scenarios for Clearwater Lake

The assessment of the aquatic effects of various deposition rates to Clearwater Lake was made using a mass balance model (22, 69). Mass balance models of this type were used in the development of strategies for the management of eutrophication of lakes by phosphorus control (70, 71, 72, 73). The principles used in these models can be applied to substances other than phosphorus.

The model predicts the rate of loss of acid neutralizing capacity (ANC) of the lake, which is in effect the acidification rate. The following assumptions were made in the scenarios presented, in addition to those previously noted (69):

i) The deposition of acid is equal to the deposition of SO_4^{2-}. An annual SO_4^{2-} deposition rate of 96 kg SO_4^{2-}/ha·yr was used as the baseline deposition. (See Section 5.1.)

ii) The assimilation of acid by the watershed of Clearwater Lake is 93% and is independent of any changes in deposition rate. The value of 93% was calculated for the four watersheds of Clearwater Lake for a two year (1977 to 1979) time period, as the difference between the measured loss of acid from the watershed (via streamflow) and the measured input of acid to the watershed by precipitation (corrected for the dry deposition of SO_2 (74)). Because there is no significant source of alkalinity in the lake or watershed, the 7% of the acid entering the lake plus that which falls directly on the lake surface in precipitation acidifies Clearwater Lake. This further implies that severely affected lakes such as Clearwater cannot recover on their own.

   The sensitivity of the model to the 93% assimilation figure was tested by varying the value from 90% to 100%. (See Table 5.2.) The results show that the length of time required to reacidify the lake is not very sensitive to this variable over the range tested.

iii) The lake is neutralized by base additions to leave residual alkalinity of 500 ueq L^{-1}, i.e. the lake's alkalinity is artificially raised to the point that the lake is (initially) not sensitive to acid precipitation.

The following scenarios were examined:

a) The alkalinity of the lake was allowed to drop from 500 to 200, 40 and 0 ueq L^{-1} coinciding with moderately sensitive, extremely sensitive and acidified lake acid sensitivity categories (75).

b) Total SO_4^{2-} deposition rate targets of 10, 20, 30, 40, 60, 80 and 96 kg/ha·yr were considered.

The elapsed time, after raising the alkalinity to 500 ueq l^{-1}, required to reacidify the lake to the final alkalinity levels specified above were calculated (69). Then the percentage reduction required in total SO_4^{2-} deposition rate (initially 96 kg/ha·yr) to meet the SO_4^{2-} deposition rate targets specified was calculated, together with the percentage reductions in SO_2 emissions required from Sudbury sources. (As presented in Table 5.1, Sudbury sources result in a deposition rate of 50 kg SO_4^{2-}/ha·yr).

The results of this exercise are presented in Table 5.3. The percentage reductions in SO_2 emissions from the Sudbury operations were determined on the assumption that the sulphate deposition rates are linearly related to the SO_2 emissions. This is a reasonable assumption given the proximity of the receptor area to the source.

The SO_2 emission 'base case' for the Sudbury area, in this exercise, is taken as the average emission rate during the period June 1977 to May 1978 for which a total sulphur deposition rate of 96 kg SO_4^{2-}/ha·yr at Clearwater Lake was estimated. This SO_2 emission rate was determined to be about 3,000 tonnes per day.

From the data presented in Table 5.3, assuming that the contribution to the deposition rates from all other sources remains constant at 46 kg SO_4^{2-}/ha·yr, the deposition targets of 10, 20, 30 and 40 kg SO_4^{2-}/ha·yr cannot be met by effecting a 100% cutback in Sudbury SO_2 emissions. On the other hand, deposition targets of 60 and 80 kg SO_4^{2-}/ha·yr can be met by effecting reductions in Sudbury SO_2 emissions by 72% and 32% respectively. However, these emission reductions from Sudbury operations would not be effective at maintaining desirable (200 ueq l^{-1}) lake alkalinity levels. Hence, in addition to significant cuts in Sudbury emissions, a reduction of other sources would be required.

Sudbury emission reductions would aid in the protection of many lakes sensitive to acid deposition (those with total inflection point alkalinity (TIA) in the 0-40 and 40-200 ueq l^{-1} range). This is supported by the data compiled in Table 5.4 which demonstrates the trend towards lower average lakewater sulphate concentrations (Clearwater Lake) with decreasing Sudbury area SO_2 emissions for the period 1973 to 1981. It has been estimated that approximately 50% of the lakes in the Sudbury district have alkalinities in these ranges. As exemplified in Section 5.1, significant benefits would be realized by concurrently effecting emission reductions for the other contributing sources which are estimated to account for 48% of the problem in this area.

5.2.2 Application of Clearwater Lake Case to Other Sudbury Area Lakes

To estimate the number of acidic lakes in the immediate Sudbury area similar to Clearwater Lake, lake survey data taken in 1981 by the Northeastern Region of the Ontario Ministry of the Environment were used. These lakes were a subset of 250 lakes surveyed on a regional basis. The selection criteria for the large lake set (37) were as follows:

1. provision of broad coverage of lakes on a regional scale;

2. representation of all potential variations in lake waters due to natural (geological) and anthropogenic (atmospheric) influences;

3. inclusion of lakes known to exhibit adverse effects, i.e., extinct or depressed fisheries;

4. suitable size to facilitate sampling via float-equipped aircraft.

Sixty-one lakes were surveyed within 50 km of Sudbury, of which 18 (30%) were acidic (TIA is less than 0 ueq l^{-1}) (76). Using data on the number of lakes organized by watershed in Ontario (77), an estimate may be made of the numbers of acidic lakes. If the extent of the affected area in the immediate vicinity of Sudbury is approximated by the watersheds 2CF, 2DA and 2DB (Figure 5.1), then a total of 5,154 waterbodies are included. Of these 1,124 have surface areas greater than 10 ha. Applying the 30% figure, one can extrapolate that 337 acidic lakes exist in the immediate area of Sudbury and 1,209 smaller acidic waterbodies exist. Given the uncertainties inherent in these calculations, estimates of 200-400 acidic lakes and a minimum of 1,200 smaller acidic waterbodies would perhaps be in order. The approximate nature of these values cannot be overemphasized.

5.3 Conclusions

On the basis of total SO_4^{2-} deposition rate and its impact on acid sensitive watersheds within about 50 km from Sudbury, the following conclusions can be drawn:

a) A deposition rate of 39 kg SO_4^{2-}/ha·yr as estimated at Muskoka-Haliburton (Table 5.1) is known to adversely affect the aquatic environment.

b) Assuming that the contributions from all other sources remain unchanged, it is not possible to reach a deposition rate of 40 kg SO_4^{2-}/ha·yr in the Sudbury area even with a 100% reduction in local SO_2 emissions.

c) In addition to significant reductions in Sudbury emissions, other means are required to restore and protect the water quality of a large number of currently acidic lakes.

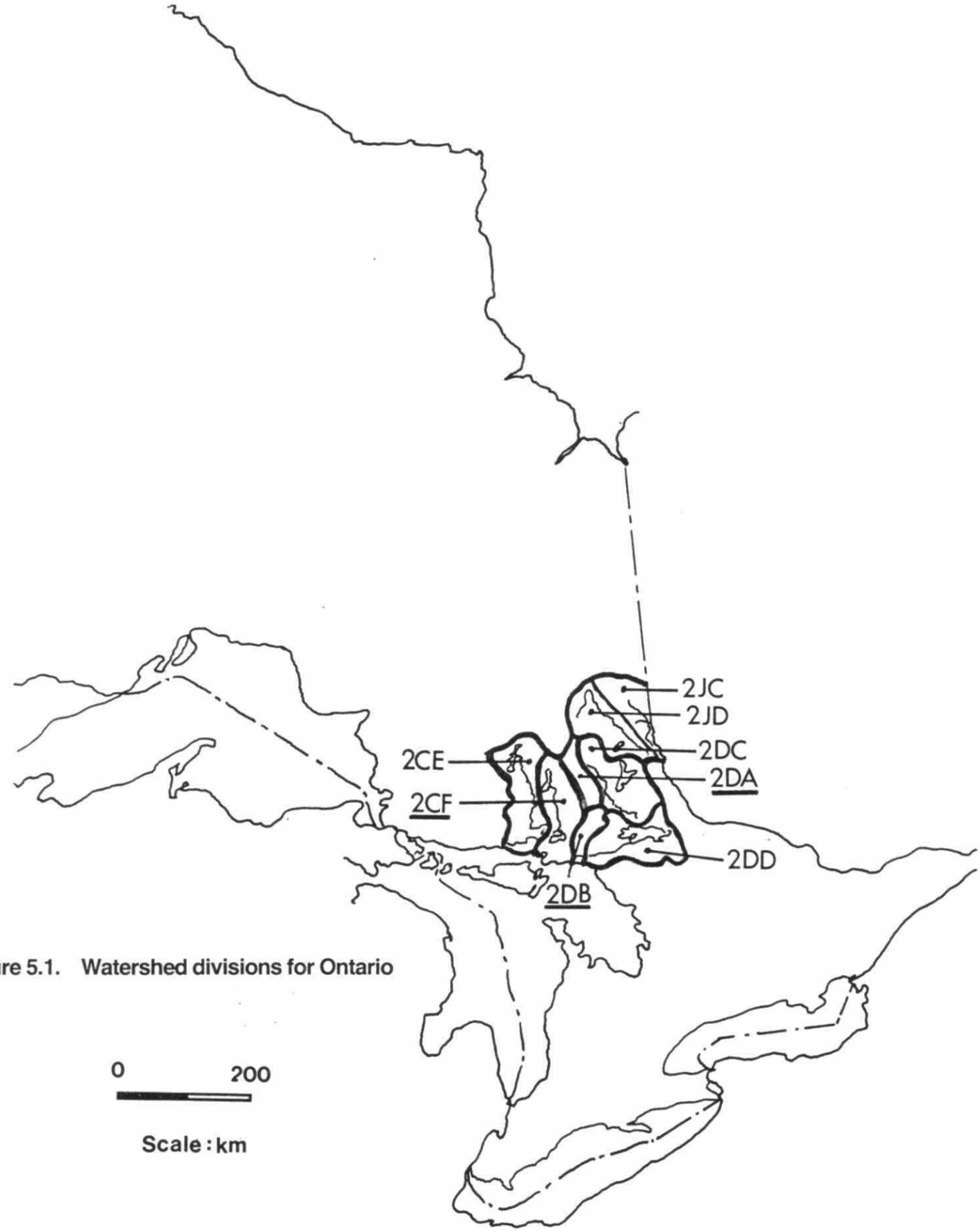

Figure 5.1. Watershed divisions for Ontario

Table 5.1. Estimate of SO_4^{2-} deposition rates in the Sudbury area and in the Muskoka-Haliburton area in Kg SO_4^{2-}/ha·yr

	Clearwater Lake		Nelson Lake		Sudbury NE+		Sudbury W++		Muskoka-Haliburton	
	All*	Sudbury**	All	Sudbury	All	Sudbury	All	Sudbury	All	Sudbury
Wet	30[a]	3[a]	30[a]	3[a]	30[a]	3[a]	30[a]	3[a]	20[b]	3[b]
Dry	66[c] (28)[e]	47[d] (9)[e]	33[d] (24)[e]	14[d] (5)[e]	124[d] (34)[e]	105[d] (15)[e]	42[d] (23)[e]	23[d] (4)[e]	19[b]	6[b]
Total	96	50	63	17	154	108	72	26	39	9

* Represents all contributing sources including Sudbury sources.
** Represents contributions to deposition from Sudbury sources alone.
\+ A location about 10 km NE of the Inco Copper Cliff smelter.
++ A location about 10 km W of the Inco Copper Cliff smelter.
a Determined from the wet deposition monitoring program for the period mid-1978 to mid-1980; represents an average within a 40 km radius of the Inco smelter; Sudbury sources contribute 10% of total wet deposition.
b Determined from modelling estimates using the long range-long term model developed by the Ministry, for 1977 SO_2 emission levels.
c Determined from watershed and lake mass balance calculations over the period June 1977 to May 1978 and model estimates for the same time period using the short range-long term model developed by the Ministry.
d Determined from modelling estimates using the short range-long term model developed by the Ministry, for the period June 1977 to May 1978.
e Determined from modelling estimates using the short range-long term model developed by the Ministry, for the period June 1978 to May 1979 (Inco shut down through most of this period).

Table 5.2. Reacidification rate calculations for Clearwater Lake

Deposition Rate (kg SO_4^{2-}/ha·yr)	40	80
Acid Retention by Watershed (%)	Time for reacidification (years)	
0.90	9.6	7.0
0.91	9.7	7.1
0.92	9.8	7.2
0.93	10.0	7.4
0.94	10.1	7.5
0.95	10.2	7.6
0.96	10.4	7.8
0.97	10.5	7.9
0.98	10.7	8.0
0.99	10.9	8.2
1.00	11.0	8.4

Model Constants:
A_o = 76.5 ha
A_d = 342.1 ha
Q = 1.47×10^9 l/yr

Alkalinity:
TIA initial = 500 ueq l^{-1}
TIA final = 0 ueq l^{-1}

Table 5.3. Lake acidity and emission reduction scenarios

INITIAL ALKALINITY (ueq l^{-1})	FINAL ALKALINITY (ueq l^{-1})	TARGET SO_4^{2-} DEPOSITION RATE kg ha·yr	ELAPSED TIME TO REACIDIFICATION (years)	% REDUCTION FROM DEPOSITION RATE OF 96 kg SO_4^{2-}/ha·yr	% SO_2 REDUCTION* SUDBURY OPERATIONS
500	200	10	3.8	90	100
500	40	10	9.8	90	100
500	0	10	15.7	90	100
500	200	20	3.6	79	100
500	40	20	8.9	79	100
500	0	20	12.8	79	100
500	200	30	3.5	69	100
500	40	30	8.3	69	100
500	0	30	11.1	69	100
500	200	40	3.4	58	100
500	40	40	7.6	58	100
500	0	40	9.9	58	100
500	200	60	3.1	38	72
500	40	60	6.7	38	72
500	0	60	8.4	38	72
500	200	80	2.9	17	32
500	40	80	6.0	17	32
500	0	80	7.4	17	32
500	200	96	2.7	0	0
500	40	96	5.6	0	0
500	0	96	6.7	0	0

* Assumptions:
(1) Deposition rate (Sudbury only) is linearly related to SO_2 emissions.
(2) SO_2 emissions contribute the majority of SO_4^{2-} in the deposition rate.

Table 5.4. Annual average sulphate content of Clearwater Lake

Year	SO_4^{2-} Concentration ($mg\ l^{-1}$)	Total SO_2 Emissions In Sudbury Basin (10^3 tonnes)
1970	N.A.+	2330
1971	N.A.	2230
1972	N.A.	1842
1973	27.8	1460
1974[1]	25.6	1474
1975	24.9	1393
1976	26.0	1410
1977	26.4	1337
1978	23.9	684
1979	22.0	496
1980	21.6	935
1981	19.6	837

[1] All samples from 1 m below surface.
+ Not available.

Note: Sulphate figures are whole lake measurements unless noted.

6. REMEDIAL MEASURES

6.1 Terrestrial Ecosystem

The problems associated with the regeneration of the stressed terrestrial ecosystems of the Sudbury area have been well documented (78). The results of intensive studies conducted from the late 1960's to the mid-1970's in areas within about 8 km south and north of the Coniston and Falconbridge smelters respectively have indicated that the major ecological impediments to the regeneration of these barren areas are micrometeorological conditions, soil acidity (reduced pH) and elevated levels of toxic metals in soils (78). Untreated soils from these barren areas have shown almost no potential for plant growth. The application of lime to these barren soils has resulted in improved germination and growth. This observed growth enhancement has been attributed to soil pH adjustment rather than to calcium addition; it appears that the principal effect of soil pH adjustment on plants is that of decreased metal toxicity. Experience gained from these studies prior to 1978 has shown that the most satisfactory form of lime used has been feed grade pulverized limestone. In addition to liming, fertilization has proven to be beneficial to varying degrees. On a single application, organic fertilizers appeared to be superior, followed by inorganic fertilizers with slow-release nitrogen, followed by inorganic fertilizers without slow-release properties.

Since 1978, a large scale land reclamation project has been carried out in the Sudbury area (79). The objective of this program was to make major aesthetic improvements in the Sudbury area by progressively revegetating lands adjacent to major transportation corridors. That year, the Vegetation Enhancement Technical Advisory Committee was formed with representation from Inco Limited, Falconbridge Limited, the Ministry of the Environment, the Ministry of Natural Resources, the Nickel District Conservation Authority, Cambrian College, Laurentian University and the Regional Municipality of Sudbury. The purpose of this Committee is to oversee the activities of the Sudbury land reclamation project.

The reclamation activities undertaken include soil pH testing, damaged site improvement, grassing, greening, and reforestation. Since soil pH adjustment is mandatory to provide potential for plant growth, a soil pH testing survey is conducted prior to grassing or greening of barren sites in order to determine the amount of lime required to adjust the pH to about 6.0. In recent years, dolomitic limestone has been applied at the rate of about 11 tonnes per hectare.

Damaged site improvements are usually performed prior to grassing and greening. This consists of a clean-up of these sites by removing dead trees and stumps, pruning of native trees and shrubs, and sometimes the removal of other debris and stones. In addition to improving site aesthetics, this procedure provides greater available soil surface area for the establishment of a vegetation cover.

The development of a grass cover, or grassing, consists of liming, fertilizing and seeding. An agricultural fertilizer (6-24-24) is being applied at a rate of about 900 kg per hectare. A seed mixture, which has proven to be successful, consists of the following percentage composition: creeping red fescue (20%) kentucky blue (15%), timothy (15%), red top (20%), tall fescue(15%), alsike clover (10%) and birdsfoot trefoil (5%). It is being applied at a rate of about 68 kg per hectare.

The development of a grass cover, at some sites, is done without seeding, through liming or a combination of liming and fertilizing. This approach, termed greening, allows the germination of native seeds in barren soils; it has proven to be quite successful.

Over the past five years, about 20,000 trees have been planted in land reclaimed areas, after the establishment of a grass cover. The tree stocks have been provided by the Ministry of Natural Resources and consist of bare root stocks, Japanese paper pot and Ontario landscape stocks (five year old trees). The predominant species used have been jackpine, red pine, white spruce, cedar, poplar and silver maple. The reforestation success rate is claimed to range from 40% to 100% (survival rate).

Finally, a regular monitoring program has been maintained in order to gauge the success of these revegetation efforts and to effect possible improvements in the methods used.

To date, the overall program has proven to be highly effective in improving the appearance and the environment of the Sudbury area.

6.2 Aquatic Ecosystem

6.2.1 Neutralization

The addition of basic calcium compounds, especially calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$), has been practised as a means of increasing fish production in coloured, acidic ponds and lakes. As part of the activities of the Sudbury Environmental Study, neutralization experiments were carried out on several acidic lakes in the Sudbury area (22). Since these lakes contain elevated levels of Cu and Ni, they differ from the experimentally neutralized lakes in Sweden. The overall

purpose of the work was to determine the effects of an increase in pH on the chemistry and biota of acidic lakes in the Sudbury area. The findings may be used to assess the impact of a reduction in the input rates of strong acids to the lakes.

Neutralization experiments were performed in Lohi, Middle, Hannah and Nelson Lakes. Clearwater Lake was used as a reference for these experiments (see Figure 4.1 for lake locations). A schedule of base additions to the study lakes, together with a breakdown of the quantities of base added, are given in Table 6.1 (22). Middle Lake received base additions ($Ca(OH)_2$ and $CaCO_3$) in 1973 only, whereas Lohi Lake received base additions in 1973, 1974 ($Ca(OH)_2$ only), and in 1975 ($Ca(OH)_2$ and $CaCO_3$). Hannah Lake was neutralized in 1975 ($Ca(OH)_2$ and $CaCO_3$) only, whereas Nelson Lake was neutralized in 1975 and in 1976 using both neutralizing agents.

Enough $Ca(OH)_2$ was added to Lohi and Middle lakes to raise the pH to about 8.0 (determined by titration), a level that was considered adequate for subsequent neutralization of the entire water column and of the top few cm of lake sediments. Calcium carbonate was simultaneously added to Middle Lake with the intent of providing a residual buffering system. The amount of both chemical compounds added to Hannah Lake per unit volume was identical to that added to Middle Lake, while the required dosages for Nelson Lake were estimated by separate titration of Nelson Lake water.

The following constitutes a summary of the results of the neutralization experiments conducted on these lakes (22):

- The pH of Middle, Lohi and Hannah Lakes was raised from approximately 4.3 to near neutrality through the additions of base. In Middle and Hannah Lakes, average pH remained greater than 6.5 until the end of the study (1980), while in Lohi Lake, the added acid neutralizing capacity (ANC) was exhausted in the spring of 1977. By 1979 the pH had decreased to 4.7. The pH of Lohi Lake decreased because:

    a) it received a higher volumetric supply of acid than did Middle and Hannah Lakes;

    b) concentrations of ANC remaining immediately after additions of base were much lower in Lohi Lake than in Middle and Hannah Lakes;

    c) fertilization of Middle and Hannah Lakes resulted in generation of more alkalinity than was generated by the biota in Lohi Lake.

- In Middle, Lohi and Hannah Lakes, 30 to 41% of the added ANC was consumed by reaction with Al^{3+}, Cu^{2+} and Ni^{2+}, 1 to 3% by hydroxylation of trace metals other than Al, Cu and Ni, 5 to 20% by direct reaction with H^{+}, and, by residual, 31 to 44% by neutralization of acidic sediments.

- Additions of base significantly reduced levels of Cu, Ni, Mn, Al and Zn in Middle, Lohi and Hannah Lakes. Metal concentrations in the lakes were controlled by pH-dependent solubility reactions, not by external input rates; hence, levels of Cu, Ni, Zn and Mn in Lohi Lake returned to pre-treatment levels after the lake re-acidified.

- Additions of base produced no long term changes in concentrations of total phosphorus (TP) or total nitrogen (TN).

- The addition of base was followed by an immediate and drastic reduction in phytoplankton standing stocks in Middle, Lohi and Hannah Lakes. Levels recovered and approached, but did not exceed, pre-treatment levels within a few months. While taxa that are characteristically dominant in non-acidic lakes (chrysophytes) replaced acid-tolerant species (dinoflagellates) after community biomasses recovered, community diversities remained well below normal for the duration of the study. Dinoflagellates did not replace chrysophytes after the re-acidification of Lohi Lake, indicating that there is at least a two year lag before communities typical of acidic lakes are re-established.

- Secchi transparency increased immediately after additions of base, accompanying the large decrease in phytoplankton standing stocks. In the long-term, however, Secchi transparency decreased by two meters in Lohi Lake after neutralization, then increased to pre-neutralization levels after the lake re-acidified. These longer term changes were not correlated with changes in phytoplankton standing stocks. The decrease in transparency after neutralization resulted in a shallower mixing zone and a cooler hypolimnion. It also reduced the depth of maximum photosynthetic activity.

- Additions of base drastically reduced zooplankton standing stocks in Middle, Hannah and Lohi Lakes. Biomass did not recover for two years in Lohi Lake and communities typical of non-acidic lakes had not been re-established four years after the additions of base, when the lake re-acidified.

- Rainbow trout were placed in submerged enclosures in Middle and Lohi Lakes after additions of base. They survived for less than four days, on average. Despite the reduction in levels of trace metals that had occurred after additions of base, levels of metals, especially Cu, were too high to allow survival of the fish.

- Additions of base raised the pH of Nelson Lake from 5.7 to 6.3. This addition significantly reduced levels of Cu, Ni, Mn, Al and Zn, but produced no short or long-term changes in nutrient chemistry or in assemblages of plankton.

- Middle Lake was stocked with smallmouth bass, Iowa darters and brook stickleback in 1976 after neutralization in 1973. Similarly, Lohi Lake was stocked with brook trout, Iowa darters and brook stickleback in 1976. Despite considerable fishing effort, none of the stocked fish were recovered. The mortality was attributed to copper toxicity.

- The effect of base additions to the fish community of Nelson Lake, while difficult to assess, suggests a qualitative improvement in the fisheries status of the lake.

6.2.2 Fertilization

Fertilization experiments performed in Canadian lakes have demonstrated that increases in nutrient supply (nitrogen (N) and phosphorus (P)) can result in increases in phytoplankton biomass and in the productivity of communities of zooplankton and fish. To determine if responses to fertilization of neutralized, acidified lakes (residually contaminated with trace metals) were similar to those of non-acidic lakes, and to improve the food base prior to introduction of fish, phosphorus was added to Middle Lake between 1975 and 1978 and, for comparison, to Hannah Lake between 1976 and 1978. To see if acidic and non-acidic lakes differ in their response to high rates of addition of nutrients, i.e. to see if symptoms of eutrophication can develop in acidified lakes, phosphorus (at much higher rates of supply) and nitrogen were added to non-acidic (pH = 6.0) Labelle Lake from 1977 to 1978 and to acidic (pH = 4.6) Mountaintop Lake from 1976 to 1978. Experimental additions provided 97% of the phosphorus supplied over the period of fertilization to Mountaintop and Labelle Lakes, 82 to 87% in Middle Lake and 79 to 82% in Hannah Lake.

The effects of these additions on the chemistry and biota of these lakes are summarized as follows (22):

- Levels of total phosphorus (TP) increased in Middle and Hannah Lakes, but annual averages did not exceed 15 $\mu g\ l^{-1}$. Additions resulted in decreases of NO_3^- from 420 to 30 $\mu g\ l^{-1}$ in Middle Lake and from 520 to 90 $\mu g\ l^{-1}$ in Hannah Lake.

- Phytoplankton biomass increased after additions of phosphorus. Chrysophytes were dominant in the spring in all years of fertilization, but dominant taxa in the summer were not predictable.

- Zooplankton biomass was also increased by fertilization, but metal toxicity apparently limited the increase. Fertilization did not encourage the re-establishment of communities typically observed in uncontaminated Precambrian Shield lakes.

- Phosphorus budgets for Mountaintop and Labelle Lakes indicated that phosphorus was transported to the sediments as rapidly in acidic as in non-acidic lakes, even at very high rates of fertilization. Ratios of concentrations of N:P in Mountaintop and Labelle Lakes were 1.7 to 3.6 times higher than ratios of supply of N:P. This indicated that rates of loss of P from the water column were greater than rates of loss of N.

- Differential uptake of NH_4^+ relative to NO_3^- was in part responsible for the decrease in epilimnetic pH that occurred over the summer in Mountaintop Lake. While pH normally increases in the euphotic zone of non-acidic lakes over the summer, in Mountaintop Lake it decreased, at one point to 4.0. In contrast, the pH of the hypolimnion increased to 6.0 at times of anoxia, most likely because of bacterial reduction of SO_4^{2-}, NO_3^- and ferric hydroxides. A portion of the generated alkalinity was re-entrained into the surficial waters at fall overturn.

- Phytoplankton biomass increased substantially after fertilization in Mountaintop Lake, indicating that acidification of lakes will not prevent the development of the large phytoplankton standing stocks that characteristically accompany increased rates of nutrient supply. Temporal changes in species composition were much smaller in Mountaintop Lake than in Labelle Lake. A single species formed 90% of the community biomass for most of the ice-free season in each year.

- Zooplankton densities increased in response to the increased phytoplankton food base in Labelle Lake. In the first year of fertilization in Mountaintop Lake, zooplankton densities increased to levels much higher than ever observed in Labelle Lake. Levels of herbivorous zooplankton were, in fact, sufficiently high that their grazing activities reduced phytoplankton standing stocks to very low levels. Zooplankton densities decreased rapidly in the summer of the second year of fertilization in

Mountaintop Lake and remained low (40 times lower than in the first year of fertilization) in the third year of fertilization. Both the large increase in zooplankton biomass in the first year of fertilization and the crash in the second and third years in Mountaintop Lake were attributable to predator/prey interactions. In 1976, densities of invertebrate predators were 40 times lower than in Labelle Lake, and zooplankton densities increased substantially in an environment virtually free of predation. Phytoplankton populations were decimated in consequence. In the second year of fertilization in Mountaintop Lake, increased prey availability in the absence of fish allowed the development of very substantial populations of Chaoborus. Chaoborus reduced zooplankton densities to very low levels. Acidification, therefore, indirectly reduced the resilience of the plankton communities of Mountaintop Lake to fertilization.

In summary, the addition of neutralizing agents to the study lakes increased pH, provided residual alkalinity and decreased trace metal levels. However, biological communities typical of those in circumneutral lakes were not reestablished over the duration of the study. Fish stocked in two of three neutralized lakes did not survive because water column trace metal levels remained too high after treatment.

Table 6.1. Neutralization of S.E.S lakes

	1973		1974		1975		1976		Total	
	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$	$Ca(OH)_2$	$CaCO_3$
Middle	20.0 (477)	13.6	-	-	-	-	-	-	20.0 (477)	13.6
Lohi	18.2 (196)	-	4.1 (45)	-	5.0 (184)	15.0	-	-	27.3 (426)	15.0
Hannah	-	-	-	-	13.0 (477)	7.5	-	-	13.0 (477)	7.5
Nelson	-	-	-	-	50.0 (58)	33.0	18.0 (24)	18.0	68.0 (82)	51.0

Note: Figures are nominal additions in 10^3 kg. Figures in parentheses are calculated additions of acid neutralizing capacity (ANC), ueq l^{-1}), correcting for assay of the neutralizing agent ($Ca(OH)_2$ - 48.7% Ca; $CaCO_3$ - 38.0% Ca) and assuming that the Mg content of the agents ($Ca(OH)_2$ - 3.37% Mg. $CaCO_3$ - 3.40% Mg) supplies ANC.

7. CONCLUSIONS

The Sudbury Environmental Study, initiated in 1973, was designed to test the assumptions that emissions from the Sudbury smelting operations had contributed to and were continuing to contribute to significant environmental deterioration in the Greater Sudbury Area.

The impact on the Sudbury environment was unique as a result of the geology of the area and the scale and duration of the mining and smelting operations.

Before summarizing specific study conclusions, it is important to recognize that, just as environmental damage does not happen overnight but, rather over many decades, environmental reclamation will slowly trace significant emission reductions. This has been demonstrated by the Sudbury experience over the decade 1970-1980 (a 50% reduction in SO_2 emissions and the concomitant improvement in the environment).

In order of emission magnitude (Table 7.1), the most significant source in the Sudbury Basin is the 381 m stack at the Inco Copper Cliff smelter which contributes anywhere from 50% to over 80% of all emissions in the Basin. The other sources in the area are the Inco 194 m IORP stack, the Falconbridge smelter 93 m stack, and low level emissions from the Copper Cliff smelter building.

Wind directions in the Sudbury area are more frequently from the west and southwest than other directions. This results in a significant influence on dispersion and dry deposition which influences the environmental impact towards the east and northeast.

The Sudbury environment is affected by contributions to deposition from non-Sudbury sources, primarily due to long range transport. For example, Sudbury sources contribute on average, within a 40 km radius, about 10% of the total wet sulphate deposition in the Sudbury area. However, the Sudbury sources' contribution to dry deposition is highly direction oriented and quite significant, ranging from 30 to 70 percent of the total dry component.

From May through to October, the tall stack at the Copper Cliff smelter is of limited effectiveness in preventing elevated ground level concentrations as plume looping occurs on warm, sunny days resulting in intermittent high ground level concentrations of sulphur dioxide.

With respect to total sulphur deposition in Ontario, Sudbury is the single most significant source region (8% of the total deposition in Sault Ste. Marie and 15% of the total deposition in Muskoka-Haliburton)(80).

The deposition of trace metals from local sources is significant. Up to 70-80% of emissions of copper and nickel are deposited within the Sudbury area (40 km).

The acute and chronic effects of SO_2 emissions on vegetation in the Sudbury area have been studied for some time. Research indicates that prior to 1972, there was significant injury to vegetation. This has been reduced to the extent that, presently, acute injury occurs infrequently, and is confined to relatively small, isolated areas and affects only those plant species most sensitive to SO_2. In order to prevent recurring injury to vegetation, some reduction in SO_2 emission levels is required.

The greatest impact on soils in the immediate Sudbury area was observed to be from copper and nickel, often found in excessive levels. Their concentrations were found to decrease with increasing distance from the smelters.

Because vegetation and soil contamination is believed to be largely historical, it is difficult to relate emission objectives for metals and terrestrial impact. It is appropriate to suggest that the burden on the terrestrial environment from metals will decrease concurrently with decreasing metal emissions and acidic deposition. However, revegetation of barren soils will come more readily through remedial programs.

There is evidence to indicate that adverse environmental impacts on the aquatic ecosystem in the Sudbury area have been significant. There may be as many as 200-400 acidified lakes and 1,200 acidified waterbodies of 10 hectares or less within 50 km of Sudbury.

The decreasing trend in sulphate levels in Clearwater Lake appears to follow reductions in Sudbury area emissions.

This observation should not be interpreted as reason to hold emissions at current levels. Despite improvements and reduced emission levels, studies show that the non-Sudbury contributions to total sulphur deposition rates in the Sudbury area are equal to loadings known to be affecting other sensitive areas. Therefore, not only are further reductions needed from Sudbury sources, but from non-Sudbury sources, as well.

The distribution of metals, particularly copper and nickel, in the lakes studied raises concerns relative to impacts on the aquatic biota. The evidence suggests that there should be a significant reduction in metal deposition in the Sudbury area of at least 90% for copper and nickel. The requirement for a reduction in metal loadings could be relaxed if acid loadings were to be reduced.

Through the experimental manipulation of lakes near Sudbury, significant improvement in water quality has been demonstrated as a result of the application of neutralizing agents. Although neutralization can raise the pH to neutrality, increase the alkalinity and lower levels of trace metals, the indigenous biota are not restored to a state resembling that of a circumneutral lake. Fish stocked in two neutralized lakes did not survive because levels of trace metals were still elevated. A qualitative improvement was observed in a third neutralized lake with lower metal levels.

Table 7.1. Percentage source contributions of major pollutants emitted in the Sudbury Basin

SOURCE	POLLUTANTS	% CONTRIBUTIONS
Inco 381 m stack (Copper Cliff) smelter	SO_2	78
	SO_4	77
	Metals	55
	Total Particulates	75
Inco 194 m stack (IORP)	SO_2	5
	SO_4	18
	Metals	32
	Total Particulates	16
Falconbridge smelter 93 m stack	SO_2	16
	SO_4	5
	Metals	4
	Total Particulates	6
Fugitive Emissions (Copper Cliff) smelter	SO_2	1-2
	SO_4	1
	Metals	9
	Total Particulates	3-4

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GLOSSARY OF TERMS

acid:	a substance capable of donating a proton (H+); on a pH scale of 0-14, substances with a pH less than 7.0 are acidic (e.g. vinegar and orange juice)
acidophil(ic):	having to do with an organism that has affinity for and grows well in an acid environment
acute vegetation injury:	visible injury which is caused by exposure to high concentrations of SO_2 during short time periods
aerosol:	dispersion in a gas of many very small particles (but not individual molecules) of a solid or liquid
alkaline:	on a pH scale 0-14, a substance with pH greater than 7.0 (e.g. ammonia, water and baking soda solution)
ambient:	in the outside environment
anthropogenic:	arising as a result of man's activity
autotrophic:	making its own food by photosynthesis, as a green plant, or by chemosynthesis, as can certain bacteria
benthic:	having to do with all the plants and animals living on or closely associated with the bottom of a body of water
biosphere:	the zone of the earth, extending from its surface out into the surrounding atmosphere, which contains living organisms; all the living organisms of the earth
bulk deposition:	comprises both wet deposition and a fraction of the particulate and gaseous material which reaches the earth's surface by dry deposition

chemoautotrophic: producing organic matter by the use of energy obtained by oxidation of certain chemicals

chronic vegetation injury: chlorotic foliar damage (as well as reductions in other growth factors) caused by exposure to variable SO_2 concentrations over long time periods

chrysophytes: yellow or golden algae

convective boundary layer: that part of the atmosphere, usually within a km or so of the earth's surface, characterized by vigorous air mixing caused by solar heating of the earth's surface

diatoms: any of a number of related microscopic algae, one-celled or in colonies, whose cell walls consist of two boxlike parts or valves and contain silica; source of food for all kinds of aquatic life

dinoflagellates: any of an order of single-celled organisms, freshwater or marine, often with a cellulose shell; some species are luminescent and some cause the red tides that are extremely toxic to marine life

dry deposition: the process by which particles such as fly ash, or gases such as sulphur dioxide or nitric oxide are deposited or adsorbed onto surfaces

electrostatic precipitator: a device for removing particulates from industrial emissions (often removal efficiencies of greater than 95% can be realized with these devices)

epilimnion: the circulating upper layer of warm water in a thermally stratified lake

eutrophication: pertaining to a lake, pond, etc. rich in plant nutrient minerals and organisms but often deficient in oxygen in midsummer

fertilization: the addition of nutrients, most commonly phosphorus and nitrogen, to an ecosystem usually resulting in increased production of biomass

fetch: the distance over which the wind has blown uninterruptedly

flash furnace: a furnace used to smelt sulphide ore concentrate by burning some of the sulphur and iron content while the concentrate is suspended in the oxidizing medium, in much the same manner that pulverized coal is burned; the concentrate and a flux material (e.g. silica sand) are injected in this furnace with oxygen or preheated air, and the smelting temperature is obtained by the 'flash' combustion of the iron and sulphur; the concentrate is made to roast and smelt itself in a single operation

fluid bed roasters: vertical chambers-usually of circular cross-section--with grate hearths through which oxygen-bearing gas, usually air, is blown; as the material to be roasted is fed to the chamber, air is blown through the grate at a rate sufficient to hold the solid particles in suspension, the mixture of air and solids having the flow characteristics of a fluid

herbivorous: feeding chiefly on vegetation

heterotrophic: obtaining food from organic material only; unable to use inorganic matter to form proteins and carbohydrates

hydrometallurgy: the recovery of metals from ores by a liquid process, as by leaching the ore with an acid

hypolimnion: the lowermost, non-circulating layer of cold water in a thermally stratified lake

isoetid: a totally submersed fern, restricted to clear softwater lakes

Kg SO_4^{2-}/ha·yr: kilograms of sulphate per hectare·year (commonly used to express atmospheric sulphur deposition rate)

leaching: pertaining to the losses of soluble matter as a result of the filtering through of water; dissolving and being washed away

linear: referring to a relationship between two quantities where one is a simple multiple of the other

macrophytes: refers to macroscopic forms of aquatic vegetation and encompasses macroalgae, stoneworts, peteridophytes (mosses and ferns) and the angiosperms (flowering plants with enclosed seeds)

methylmercury: biologically available form of mercury produced by microorganisms; at pH less than 7 it occurs as CH_3Hg^+ which is a powerful neurotoxin in man, is concentrated up the food chain and is also absorbed by fish through their gills

microfauna: arbitrary designation (based on size) for microscopic animals (e.g. zooplankton)

microflora: arbitrary designation (based on size) for microscopic vegetation (e.g. algae)

micromorphological: the microscopic study of form or structure

microns: a unit of length equal to one millionth of a meter, or one thousandth of a millimeter

morphometry:	shape, in a lake defined by depth and area
necrosis:	death of plant tissue, as from disease, frost, etc.
neutralization:	mixing of acidic and alkaline materials so as to produce a pH close to 7
oligotrophic:	designating a pond or lake, etc. poor in plant nutrient minerals and organisms and rich in oxygen at all depths
oxidation:	a reaction in which substances combine with atmospheric oxygen
periphyton:	refers to microfloral growth upon substrata
pH:	a logarithmic measure of the hydrogen ion concentration on a scale ranging from 0 to 14; used to gauge the acidity or alkalinity of a solution
phytoplankton:	plankton consisting of plants, as algae
plume modelling:	mathematical descripition of dispersion of gas and particulates inside the plume
podzolic soil:	refers to a major soil type of northern regions, characterized by a strongly acid, infertile humus underlying a thin mat of leaves and decaying vegetation
point of impingement:	point at the ground first contacted by the plume
profundal:	refers to sediments on lake bottoms that are fine and free of vegetation; occur in the deepest parts of lakes
pyrrhotite:	any of several magnetic, bronze-coloured, lustrous native sulphides of iron, often containing small amounts of copper, cobalt and nickel

reverberatory furnace:	furnace or kiln in which ore, metal, etc. is heated by a flame deflected downward from the roof
roasting:	the operation of heating sulphide ores in air to convert to oxide; sometimes the sulphur-bearing gases produced are used to make sulphuric acid
roasting-briquetting process:	a process in which the product of roasting (i.e. calcine) is shaped into briquets (or pellets)
rotifers:	members of the large class Rotifera, mainly freshwater, microscopic aquatic organisms
secchi transparency:	is the mean depth of the point where a weighted white disk 20 cm in diameter disappears from view when lowered and reappears into view when raised, viewed from the shaded side of a vessel
slag:	the fused refuse or dross separated from a metal in the process of smelting
sphagnum:	any of a genus (Shagnum) of whitish gray masses found in damp places, bog or peat mosses
surficial:	the exterior part or face of anything
taxa:	the major groups that plant and animal organisms are systematically assigned to
tissue chlorosis:	the blanching of plant tissue usually resulting from exposure to elevated concentrations of sulphur dioxide
tonnes:	accepted common usage for a megagram which is approximately 2,200 lb.
trophogenic:	the specific stratum of a lake in which photosynthetic production occurs

ueg l^{-1}: micro equivalents per litre; one millionth of a gram equivalent weight per litre of precipitation

ug l^{-1}: micrograms per litre; unit commonly used for expressing concentrations of substances in precipitation, i.e. 1 mg (millionth of a gram) per litre of precipitation

wet deposition: removal (scavenging) during precipitation of suspended or gaseous material from air to the earth's surface

zooplankton: the animal component of freshwater plankton, dominated by three major groups Rotifera, Cladocera and Copepoda

Chemical Symbols

Al	-	aluminum	**Mn**	-	manganese
Ca	-	calcium	**Na**	-	sodium
Cd	-	cadmium	**NH_4**	-	ammonium
Cl	-	chlorine	**Ni**	-	nickel
Cr	-	chromium	**NO_3**	-	nitrate
Cu	-	copper	**Pb**	-	lead
Fe	-	iron	**S**	-	sulphur
H^+	-	hydrogen ion	**SO_2**	-	sulphur dioxide
H_2SO_4	-	sulphuric acid	**SO_4**	-	sulphate
HNO_3	-	nitric acid	**SO_4^{2-}**	-	sulphate ion
K	-	potassium	**Zn**	-	zinc
Mg	-	magnesium			

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